



Application of zeolites in organic waste composting: A review

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ABSTRACT

While composting is one of the sustainable solutions for the recycling of organic solid waste (OSW) however, it has some drawbacks that need to be addressed properly. For instance, nitrogen loss, mobility of heavy metals (HMs), greenhouse gases emissions, low productivity, and antibiotic-resistant genes enrichment are some of the technical issues of traditional composting processes. The application of zeolite and other additives to the OSW composting process is a very interesting interdisciplinary research topic that are studied by many researchers worldwide. This review intends to discuss the latest advancements on the applications of zeolites to the OSW composting processes and the its effect on the compost quality, soil remediation, nutrient management and plants growth. According to the published reports, modification of OSW compost with zeolite not only improves physicochemical properties of the compost product but also enhances microbial activities by promoting OSW decomposition and reduce the duration of the composting process. Furthermore, zeolitic additives can reduce greenhouse gases and ammonia emissions of the composting process. Zeolite-modified compost has reduced total and available HMs and reduced antibiotic resistance genes. Zeolite can upgrade the compost quality by enhancing maturity, and decreasing salinity. Last but not least, zeolite contributes to the optimization of anaerobic digestion for the production of biogas. Compost modified with zeolite exhibited improved crop yield and water retention and prevent soil nutrient losses. Overall, addition of natural zeolites to composting products are beneficial to agricultural soils and for soil remediation purposes. It is noteworthy that the addition of zeolitic aluminosilicate to soil might change the soil texture in the long term. Therefore, more in-depth researches are necessary to evaluate the cumulative effect of the addition of zeolitic minerals to agricultural lands.

1. Introduction

Increasing global waste production is driven by urbanization and population, and economic growth (Zorpas et al., 2017). The exponential growth of the economy and the rise of developing countries leads to the rapid growth of organic solids waste (OSW) production that includes household solid waste, sewage sludge, green waste, animal manure, and agricultural waste. A World Bank report (Hoorweg and Bhada-Tata, 2012) on waste generation (projection for 2025) indicated that a continual increase in waste production in all regions is expected (Table 1).

While anthropogenic OSW streams contain valuable nutrients and

organic matter (OM), they also contain various types of potentially toxic materials and compounds such as heavy metals (HMs) and pathogens. Inappropriate disposal of these OSW leads to numerous environmental and public health problems resulting from generated leachate, greenhouse gas (GHGs) and odor emission (Wang et al., 2018a, b; Waqas et al., 2018). Studies at waste management sites and landfills have pointed out that more than 50% of wastes produced by households and small-scale industries are organic wastes that can be recycled and reused as compost (Chatterjee et al., 2013). Conventional landfilling has serious environmental issues such as producing toxic leachate, and odorous toxic gasses. Composting is considered as one of the most widely-used eco-friendly and economical practical processes for OSW management

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that can stabilize OM and nutrient that can be used as organic fertilizers and/or as soil conditioners (Chan et al., 2016; Hamidpour et al., 2012; Meng et al., 2016). Composting offers a solution to mitigate some of these environmental concerns. During the composting process, organic materials break down with the help of microorganisms making compost, which is a nutrient rich material for soil amendment purposes. The organically bonded nitrogen (N) on OSW-that is not accessible to plants-will be converted to the plant accessible forms of N (i.e. ammonium hydroxide, ammonium nitrate, and ammonia), pathogens and weed seeds will be killed and malodors will be reduced, and water content of the final product will be optimized. Composting has other benefits such as the production of value-added products, reduction of mass and volume (i.e. improved handling) and decreasing of the environmental pollution (Bernal et al., 2017; Wang et al., 2018a). In addition, the application of compost in the agricultural sector can contribute to sustainable soil health (Kamyab et al., 2015). The most significant factor affecting the application of compost for agricultural purposes is the physicochemical property (quality) of the final products (Goyal et al., 2005). According to the European Waste Framework Directive (2008/98/EC), composting can prevent waste from entering the residual waste stream. According to European Landfill Directive (1999/31/EC), progressive reduction of landfilling of biodegradable municipal waste is projected for 2020 landfilling to be 35% of the volume landfilled in 1995. To achieve the goal, different approaches such reduction of waste generation (particularly food waste) and promoting home composting are suggested and encouraged (Zorpas et al., 2018).

Using compost as soil amender has many benefits including but not limited to increasing soil OM, providing plentiful of vital nutrients to plants, enhancing soil structure and sustainable water management practice. Despite all of the benefits of composting however, traditional composting processes have some drawback that needs to be addressed (Wang and Zeng, 2018). For instances, N loss through ammonia (NH₃) volatilization-that is accounted for up to 50% of the initial total N-is one of the main atmospheric pollutants during the composting process. Nitrogen losses mainly occur in the thermophilic phase of composting process resulting a final product with the reduced nutrient content (Chan et al., 2016; Gholamhoseini et al., 2013; Jeong and Kim, 2001; Wang and Zeng, 2018). Leaching out of soluble N-bearing products produced during the composting process as well as washing out of the compost nutrients immediately after land application may result in the eutrophication of water bodies, which is a fast growing environmental challenge (Chen et al., 2015; Kithome et al., 1999; Li et al., 2013; Castan et al., 2016; Chatterjee et al., 2013). High bioavailability and easy leachability of HMs in the mature compost increase toxicity of HMs in final compost leading to contamination of soil and water bodies (Liu et al., 2017; Stylianou et al., 2008; Wang and Zeng, 2018; Wong and Selvam, 2006). Numerous technical and scientific reports on total concentrations of HMs in composts produced from municipal solid waste and green waste revealed that most of the composting products contain a

high level of HMs, irrespective of the source of OSW. HMs will gradually accumulate in soils as a result of multiple and long term applications of composting products (Smith, 2009). Emission of GHGs such as methane (CH₄) and nitrous oxide (N₂O) during the composting process lead to air pollution and contribute to global warming. Last but not least, the presence of residual of herbicides, pesticides, antibiotics, hormones and other pharmaceuticals should be considered as a serious concern that is not being addressed in traditional composting processes (Liu et al., 2017; Wang and Zeng, 2018). These concerns should be considered as restricting factors for wider applications of traditional OSW composting products.

In order to address some of the above-mentioned drawbacks of traditional composting processes, scientists are considering a wide array of techniques and approaches. Adjusting/controlling composting parameters such as temperature, moisture content and C/N ratio, as well as using different chemicals, mineralogical and biological additives are studied to improve quality of final composting products (Wong et al., 2017). By improving the quality of the final products using different techniques, potential environmental risks of using composting products can be significantly decreased (Wang and Zeng, 2018). Different factors such as type and properties of organic wastes, aeration/mixing, temperature, humidity, pH, and microorganisms can affect NH₃ emissions of a composting process, in which modifying one parameter may affect others (Wong et al., 2017). Often the methods applied to minimize NH₃ losses may result in a reduction of the organic degradation rate, thus increasing the duration of composting process. Considering the composting optimum condition, there is not much room to reduce the N losses through modification of the process parameters. Therefore, using additives to trap (uptake) the released NH₃ seems to be a very promising tactic (Wong et al., 2017). Different types of compounds have been used as potential additives in order to decrease NH₃ emission and improve the quality of final compost product. Compounds such as lignite (Chen et al., 2015), alum (Lefcourt and Meisinger, 2001), carbon-base products (glucose, sucrose and straw powder) (Li et al., 2013), medical stone (Wang et al., 2017a), glucose, sucrose, starch (Meng et al., 2016), biochar (Awasthi et al., 2017a,b; Wang et al., 2017b), clay (Witter and Lopez-Real, 1988), lime with struvite salts (Wang et al., 2018c), magnesium and phosphate (Lee et al., 2009), phosphogypsum (Lim et al., 2017), bentonite (Li et al., 2012; Wang et al., 2016, 2017c; Prasai et al., 2018), hydrothermally treated lignocellulose (Nakhshiniev et al., 2014), earthworms (Wang et al., 2014) and natural zeolite (Awasthi et al., 2016a, 2016b; Bernal et al., 1993; Gholamhoseini et al., 2013; Lefcourt and Meisinger, 2001; Stylianou et al., 2008; Turan and Ergun, 2008; Wang et al., 2017b, c; Wang et al., 2018a; Witter and Lopez-Real, 1988) are studied as potential additives that could improve the compost quality. Some of these additives resulted in significant decrease in N loss and NH₃ emission during the composting process. Furthermore, they may help to control nutrients losses of the composting products after application to the agricultural lands.

Table 1
Global waste generation projections by 2025.

Region	Available Data			Projections for 2025			
	Total Urban Population millions	Urban waste generation		Projected population		Projected urban waste	
		Per capital (Kg/capital/d)	Total (t/d)	Total Population millions	Urban Population millions	Per capital (Kg/capital/d)	Total (t/d)
AFR	260	0.65	169119	1152	518	0.85	441840
EAP	777	0.95	738958	2124	1229	1.5	1865379
ECA	227	1.1	254389	339	239	1.5	354810
LCR	399	1.1	437545	681	466	1.6	728392
MENA	162	1.1	173545	379	257	1.43	369320
OECD	729	2.2	1566286	1031	842	2.1	1742417
SAR	426	0.45	192410	1938	734	0.77	567545
TOTAL	2980	1.2	3532252	7644	4285	1.4	6069703

AFR: Africa Region, EAP: East Asia and Pacific, ECA: Europe and Central Asia Region, LCR: Latin America and the Caribbean region, MENA: Middle East and North Africa region, OECD: Organization for Economic Co-operation and Development, SAR: South Asia region.

Published technical reports and scientific papers are ascertained that using of natural mineral additives such as zeolites are a more effective, less expensive and therefore more practical approach for development of a more environmentally friendly composting process and to improve the quality of the final product. Zeolites are natural crystalline aluminosilicates belonging to the tectosilicates class of minerals with a porous three-dimensional frameworks made of SiO_4 and AlO_4 tetrahedral.

The aluminum ion is small enough to occupy the position in the center of the tetrahedron of four oxygen atoms, while the isomorphous replacement of Si^{4+} by Al^{3+} produces a negative charge in the lattice. The net negative charge can be balanced by alkali and alkaline earth metals cations (Ca, Ba, Na, or K). These cations are mobile, therefore exchangeable with other cations such as ammonium (NH_4^+), lead, cadmium, zinc, manganese in the surrounding solution in a selective manner (Erdem et al., 2004; Ramesh and Reddy, 2011). Porous structure, high surface area, ion exchange and adsorption-desorption characteristics of natural zeolites make them a very attractive class of aluminosilicate materials for environmental applications such as immobilization of different toxic elements (Ghasemi et al., 2019; Ramesh and Reddy, 2011), dye removal (Aghajari et al., 2019), treatment of petroleum wastewater (Ghasemi et al., 2016), and aquaculture industry (Ghasemi et al., 2018). Natural clinoptilolite is the most abundant natural zeolite that being studied and used for agricultural applications such as developing modified composting products. Clinoptilolite possesses two types of porosities known as primary and secondary porosities. The primary porosity can be defined as microporosity presented by nanotube system of the clinoptilolite aluminosilicate framework. Macroporosity and mesoporosity are the secondary porosity (Ben-Mansour et al., 2015). Heterogeneity and hierarchic nature of clinoptilolite porosity are illustrated in Fig. 1. Natural zeolites-mainly clinoptilolite-have been extensively used in conventional and advanced composting (Kazamias et al., 2017) and vermicomposting

(Alavi et al., 2017) processes that will be discussed in details in this review paper.

Although the composting could efficaciously recycle the OSW, it still has some drawbacks such as N loss, high mobility of HMs, GHGs emission, the low quality of compost and antibiotic-resistant gens enrichment. To improve the compost quality and decrease the above-mentioned adverse effects, the addition of additives such as zeolite are being studied. To the best of our knowledge, the role of zeolite on some characteristics of compost quality and the effect of compost containing zeolite on soil and plant characteristics are not fully addressed. Thus, this work is aimed to critically review the most recent publications of the applications of natural zeolites and their modified forms to improve OSW composting processes. This main objective of this review is to discuss the effect of compost containing zeolites in agriculture and to provide some insights for future research directions on using natural zeolites and their modified forms in composting processes.

2. The effect of zeolite on the OSW composting products

2.1. Reducing of ammonium (NH_4^+) leaching, NH_3 and GHGs emissions of composting process and salinity of the final product

Emissions of NH_3 , N_2O , CH_4 and volatile organic compounds are significant environmental concerns of the composting processes (Tsai et al., 2008). Zeolitic minerals have been studied to reduce N losses (e.g. NH_4^+ and NH_3), and the GHGs emissions during the composting process (See Table 2).

Addition of different dosage of zeolites to the composting process is recommended mainly because of difference in feedstock composition. The clinoptilolite zeolite was studied for trapping NH_3 gas during the composting process of a slurry mixture of straw and pig manure. Using 53 g of zeolite per kg of composting material could reduce the N-loss by

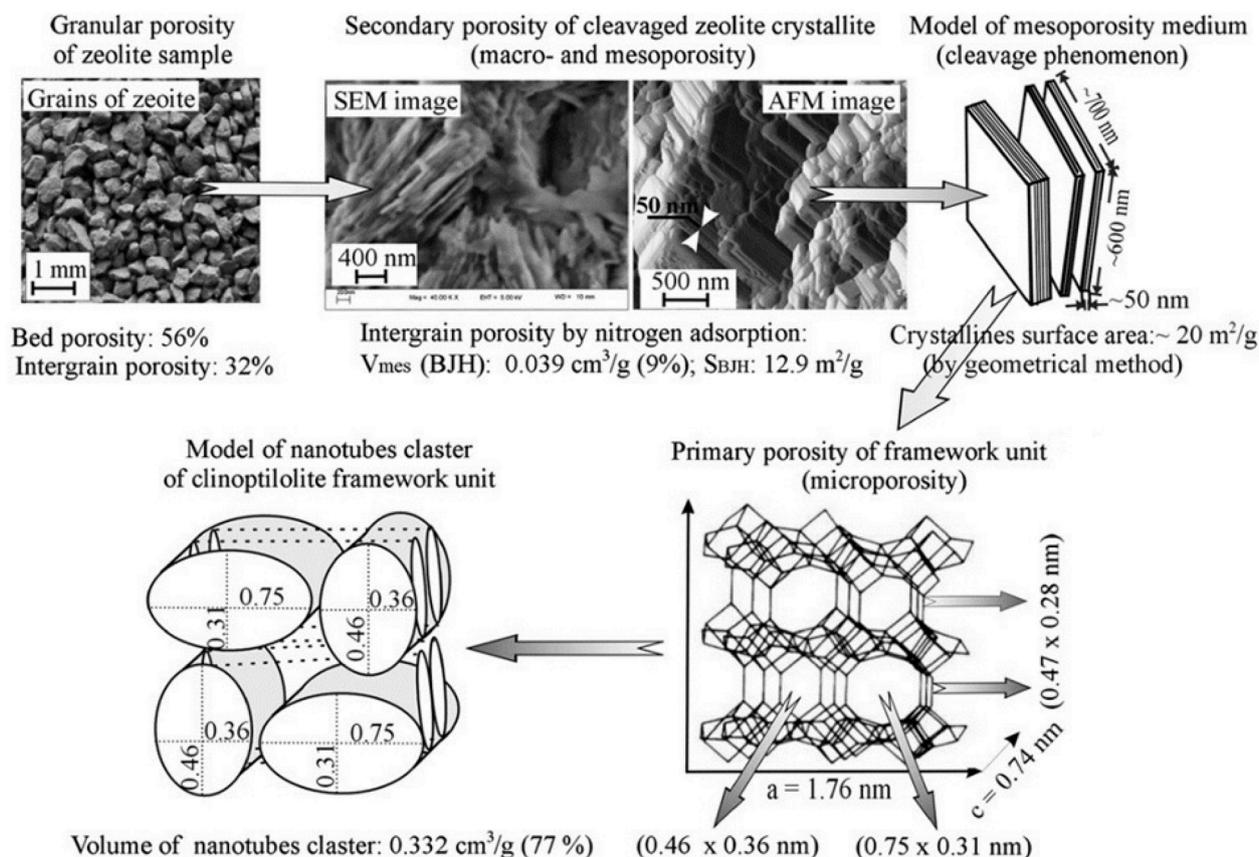


Fig. 1. Hierarchic and hierarchic of clinoptilolite porosity (reproduced by permission from Sprynskyy et al., 2010).

Table 2
Effect of zeolite on the reduction of NH₃ and GHGs emission of composting processes.

Type/source of composted material	Country	Reference
Straw-pig slurry	United Kingdom	Bernal et al. (1993)
Poultry manure	New Zealand	Mahimairaja et al. (1994)
Sewage sludge	Sweden	Witter and Lopez-Real (1988)
Poultry manure	Canada	Kithome et al. (1999)
Dairy slurry	Canada	Lefcourt and Meisinger (2001)
Pig slurry	Slovak Republic	Venglovsky et al. (2005)
Municipal solid waste	Turkey	(Turan, 2008; Turan and Ergun, 2008)
Food waste-straw mixture	Amman	Al-Jabi et al. (2008)
Poultry litter	Turkey	Turan et al. (2009)
Cattle manure	Iran	Joghan et al. (2010)
Sludge-straw	Spain	Villasenor et al. (2011)
Manure	Iran	Gholamhoseini et al. (2013)
Gelatin industry sludge, organic fraction of municipal solid waste and poultry waste	China	Awasthi et al. (2015)
Co-composting of paddy husk and chicken slurry	Malaysia	Latifah et al. (2015)
Green waste consisting mainly of fallen leaves and branch cuttings	China	Zhang and Sun (2015)
Food waste (bread, boiled rice, cabbage, and boiled pork)	Hong Kong	Chan et al. (2016)
Dewatered fresh sewage sludge	China	(Awasthi et al., 2016a,b)
Leftover food-rice hulls	Japan	Mardini et al. (2016)
Co-composting of sewage sludge and wheat straw	China	Wang et al. (2017c)
Household food waste	Greece	Margaritis et al. (2017)
Livestock manure	Korea	Lim et al. (2017)
Pig manure	China	Wang et al. (2017b)
Sewage sludge	China	(Awasthi et al., 2017a,b)
Cobb broiler and Bond Brown layer birds	Australia	Prasai et al. (2018)
Pig manure mixed with wheat straw	China	Wang et al. (2018c)
Municipal solid waste	Iran	Taheri Soudejani et al. (2019a)
Pig manure	China	Mao et al. (2019)

80% (Bernal et al., 1993). A 2–4 cm thick layer of natural clinoptilolite zeolite is placed on top of the sewage sludge compost pile for effective adsorption of volatilized NH₃ that enhanced the Kjeldahl N content of the compost by 25% (Witter and Lopez-Real, 1988). In other study composting of dairy slurry with 6.25% zeolite decreased NH₃ emission by 50% (Lefcourt and Meisinger, 2001). Al-Jabi et al. (2008) reported that a layer of 500 g of zeolite on a mesh tray reduced NH₃ losses by 41% of initial total N of starting organic materials made of a mixture of food waste and straw. They reported that the efficiency of the zeolite in adsorbing NH₃ was decreased during the composting process probably because of water adsorption that might reduce zeolite adsorption capacity toward ammonia (Al-Jabi et al., 2008). Joghan et al. (2010) reported that the addition of 10% natural zeolite (w/w; dry weight basis) reduced N leaching during a manure composting process. The N percentage of the final products with and without zeolite was 2.1% and 1.7%, respectively (Joghan et al., 2010). It is reported that addition of 14–21% (w/w, dry weight basis) of natural clinoptilolite zeolite could improve NH₄⁺, available N, organic N and total N of a manure compost (Gholamhoseini et al., 2013). Addition of 10% (w/w, dry weight basis) of commercial zeolite (most likely natural clinoptilolite) is enriched nitrifying bacteria consortium leading to a decreased N loss during co-composting of a mixture of gelatin industry sludge combined with an organic fraction of municipal organic solid waste and poultry waste (Awasthi et al., 2015). Latifah et al. (2015) reported that by incorporating of 5% (w/w, dry weight basis) of clinoptilolite zeolite into the co-composting of paddy husk and chicken slurry the total N, NH₄⁺, and

NO₃⁻ of the compost were increased. They attributed the increase to the zeolite affinity for adsorbing NH₄⁺ ions and NH₃ molecules (Latifah et al., 2015). Addition of 5% and 10% (w/w, dry weight basis) of a mixture of clinoptilolite and struvite during the food waste composting process (A mixture of bread, boiled rice, cabbage, and boiled pork in the ratio of 13:10:10:5) resulted in a decrease in salinity and pH and an increase in germination index of the final product (Chan et al., 2016). NH₃ losses was decreased by 18% during a zeolite–struvite composting process attributed to the adsorption of NH₃/NH₄⁺ by zeolite combined with possible co-participation of NH₄⁺ into struvite crystals (Chan et al., 2016). It is reported that the addition of 30% of zeolite and 1% lime (w/w, dry weight basis) to the dewatered fresh sewage sludge could remarkably decrease CH₄, N₂O and NH₃ emissions during the composting process. Decreasing of NH₃ emission is attributed to the addition of zeolite as a bulking agent that can increase the activity of NH₃ assimilating microorganisms and supply proper aeration (Awasthi et al., 2016a). During the composting process of dewatered fresh sewage sludge (DFSS), the addition of 10% zeolite mixed with biochar reduced the NH₃ emission remarkably and increased the enzymatic activity. Zeolite and biochar mixture reduced the CH₄ and the N₂O emissions by 95.34% and 97.28%, respectively. It is suggested that biochar and zeolite can potentially improve the DFSS composting by mitigating N loss and GHGs emission (Awasthi et al., 2016b). According to Mardini et al. (2016), by increasing the dosage of granular zeolite from 1.6% to 47.2% (w/w, dry weight basis), NH₃ emission significantly decreased from 979 ppm to 127 ppm. Addition of 31.5–47.2% of zeolite was recommended as the optimum dose for maximum reduction of NH₃ emission (Mardini et al., 2016). It is reported that adding 1% and 2% (w/w) of clinoptilolite zeolite to the pig slurry compost can increase the porosity of the compost and the temperature of the composting process. It can also decrease the pH levels for most of the thermophilic stage that can be attributed to the affinity of zeolites to NH₄⁺ ions (Venglovsky et al., 2005). NH₃ adsorption efficiencies of a mature compost containing 5% and 10% (w/w, wet weight basis) zeolite improved by 74.94% and 87.98%, respectively (Turan, 2008; Turan and Ergun, 2008). Zhang and Sun (2015) demonstrated that addition of 15% and 25% (w/w, dry weight basis) clinoptilolite zeolite, could decrease the NH₃ emissions through adsorption and ion exchange during the thermophilic phase of composting of a mixture of leaves and branch cuttings (Zhang and Sun, 2015). Using zeolite decreased the CH₄ emission in the thermophilic stage of sewage sludge composting, which can be attributed to adsorption characteristic of zeolite. (Awasthi et al., 2016a). Addition of 10% biochar, 10% zeolite and 2% wood vinegar during the composting process of a mixture of pig manure and wheat straw, the NH₃ and GHGs losses could be reduced by 74.32% and 81.10%, respectively (Wang et al., 2018a).

Compared to other natural absorbents, zeolite could reduce more NH₃ and other GHGs emissions. Zeolite was a more effective NH₃ and NH₄⁺ adsorbent than soil during the composting of poultry manure by reducing NH₃ loss by 60% (Mahimairaja et al., 1994). A poultry manure was co-composted using different additives including natural zeolite (25–60% by dry weight basis), coir, clay, Al₂(SO₄)₃, CaCl₂, CaSO₄, MgCl₂, and MgSO₄. Zeolite and coir were the most effective additives for decreasing NH₃ losses during composting of poultry manure. The addition of 60% zeolite to poultry manure decreased NH₃ emissions by 44.3% (Kithome et al., 1999). By using 10% of natural zeolite, removal efficiency for volatile organic compounds on poultry manure composting was higher compared to the treatments containing expanded perlite, and expanded vermiculite (Turan et al., 2009). Villasenor et al. (2011) added 10%, 25% and 40% (w/w) of clinoptilolite from different sources (i.e. Klinolith and Zeocat) and a mordenite to a sludge-straw composting process. Addition of mordenite resulted in highest carbon loss (58%), while the clinoptilolite samples were effective in reducing NH₄⁺ loss significantly. Zeocat sample exhibited the highest NH₄⁺ retention capacity that improved by increasing of the Zeocat dosage. Natural zeolite can be also used as bulking agents to improve the sludge compost

porosity (Villasenor et al., 2011). Home composting of kitchen organic waste could be improved by using mineral additives such as zeolite and perlite. The use of 10% of natural zeolite (w/w) improved the physical properties of the compost by enhancing the porosity leading to improved aeration as well as improved moisture control because of large water holding capacity (WHC) of zeolite. Besides, zeolite reduced the total N losses due to NH_3 and NH_4^+ adsorption in comparison to other additives such as wood chips, vermiculite, and perlite (Margaritis et al., 2017). Combining sawdust as a bulking agent with 25% of clinoptilolite zeolite (w/w, dry weight basis) was effective in decreasing CO_2 emission as well as total N, carbon, and dry matter losses of a cattle manure composting process. However, they did not find any evidence that zeolite can suppress NH_3 volatilization (Lim et al., 2017). While they did not explain the cause of their abnormal observation, their data is not supported by other scientific reports on the zeolite-modified composting processes. Addition of 10% biochar, 10% zeolite (w/w, both dry weight basis) to the pig manure composting process reduced the N loss remarkably. The highest mitigation of NH_3 (63.40%) and NO_2 (78.13%) emissions were observed in the biochar+zeolite treatment. By considering OM transformation, N conservation, and compost quality, they concluded that using a combination of biochar and zeolite was the most effective treatment for the studied pig manure composting process (Wang et al., 2017b). Awasthi et al. (2017a) reported that using a combination of biochar and zeolite additives could improve dewatered fresh sewage sludge composting process. The quality of the process and the final compost were improved in terms of CO_2 emissions, electrical conductivity, temperature, phytotoxicity, water-soluble and total macro-nutrient content, and WHC. They reported that using zeolite (10%, 15% and 30% w/w, dry weight) can increase the NH_4^+ retention in the final product compared to biochar (12%). They attributed this observation to the zeolite affinity to trap NH_4^+ ions through an ion exchange mechanism (Awasthi et al., 2017a). Prasai et al. (2018) observed that NH_3 content of chicken manure composted with biochar or zeolite (1%, 2% and 4% w/w) was higher compared to those of composted with bentonite or without additives. (Prasai et al., 2018). Wang et al. (2017c) reported that the zeolite could sufficiently buffer the pH and increase the temperature of co-composting process of a sewage sludge and wheat straw. The zeolite addition decreased NH_3 and GHGs emission as well. The observed that addition of 10% zeolite (w/w, dry weight basis) resulted in the maximum reduction of the GHGs emission (88.45%) and minimum N loss (28.80%) compared to the Ca-bentonite and medical stone treatments (both 10% w/w, dry weight basis). They recommended that addition of 10% zeolite could be considered optimized amount for improving the quality of sewage sludge composting product (Wang et al., 2017c). The effects of several additives on greenhouse gas emission reduction and bacterial community change of pig manure composting was studied (Mao et al., 2019). They concluded that-compared medical stone and Bamboo biochar-addition of zeolite exhibited higher efficiency in reducing N_2O emission and improving N conservation, which can be attributed to zeolite porosity and its effect on increasing the pH of the composting mixture (Mao et al., 2019).

According to Taheri Soudejani et al. (2019a), a Mg-modified clinoptilolite was more effective than the natural zeolite for retention of N in a municipal solid waste composting product. They suggested that ion exchange and struvite crystallization (co-precipitation) are two mechanisms that are involved in trapping NH_4^+ ions. Compared to the compost without zeolite, the addition of 15% (w/w, wet weight basis) natural and Mg-modified zeolite increased the NH_4^+ retention by 64.51 and 110.10%, respectively. Increasing of the zeolite dosage from 5% to 15% resulted in increasing of the total N retained in the final compost produced (Taheri Soudejani et al., 2019a).

Studies confirmed that using zeolite will decrease the salinity of the compost because of the high affinity of zeolite for cations (Latifah et al., 2015). Turan (2008) reported that the salinity uptake efficiencies of poultry litter compost containing 5% and 10% (w/w, wet weight basis) of natural zeolite were 66.64% and 88.92%, respectively (Turan, 2008).

Chan et al. (2016) reported that struvite composting can increase the salinity of mature compost. However, the addition of 10% zeolite (w/w, dry weight basis) can decrease the salinity of struvite composting products by 56% mostly through the uptake of cations including NH_4^+ ions (Chan et al., 2016). Mg-modified zeolite was more effective than the natural one to reduce the salinity and pH of municipal solid waste compost due to higher cation exchange capacity (CEC) of the Mg-modified zeolite. The application of natural and Mg-modified zeolite reduced the salinity level of the final product by 32.13 and 41.25%, respectively (Taheri Soudejani et al., 2019a). It has been reported that zeolites can decrease soluble phosphorous by more than 50% however, the mechanism is not further elaborated (Lefcourt and Meisinger, 2001).

2.2. Effects of zeolite on antibiotic resistance genes (ARGs) and degradation of organic matter

Some of OSW composting products such as sewage sludge and manure composts might be contaminated with ARGs. Direct application of ARGs contaminated composts into the agricultural lands increases soil ARGs causing damage to the ecosystem (Peng et al., 2018; Su et al., 2015; Wang et al., 2018b). Rahube et al. (Rahube et al., 2014a,b) reported that field application of sewage sludge increased the presence of ARGs in vegetables causing human health risk. Addition of natural zeolite during the composting process may help with the ARGs removal. The porous structure of natural zeolite could expand the space between the microbes or decrease the rate of microbial contact, which is the initial step of conjugation. The effect of natural zeolite on ARGs reduction/removal could be also associated with the reduction of the rate of microbial contact, and then horizontal gene transfer through conjugation (Zhang et al., 2016). Natural zeolite may change the bacterial community structure and reduce the Firmicutes bacteria, which are the most significant potential host bacteria for ARGs. This can reduce the ARGs during chicken manure composting (Peng et al., 2018). As it can be seen in section 2.4, zeolite has been commonly used to reduce bioavailability of HMs, which are considered to be co-selection factors for antibiotic resistance (Baker-Austin et al., 2006). The passivation of HMs by natural zeolite addition may reduce the co-selection of HMs to ARGs resulting in the ARGs reduction (Zhang et al., 2016, 2018). Scientific and technical data on the effects of zeolite on ARGs is very limited. Zhang et al. (2016) reported that using 1% (w/w) of natural zeolite during a sludge composting process could decrease the total ARGs copies by 1.5% due to the reduction of conjugation and co-selection of HMs caused by natural zeolite. The amount of added zeolite was slightly more than of those of nitrification inhibitor. Physical changes of the sludge composting inhibited the microbial activity rather than changing the evolution of the structure of the bacterial community. Their impacts on the alterations in the bacterial community are not completely known (Zhang et al., 2016). Peng et al. (2018) reported that the application of 5% (w/w wet weight basis) natural zeolite to a chicken manure composting could remove up to 58.9% of the total ARGs copies and enhanced the removal of pathogenic bacteria (Peng et al., 2018). Furthermore, using zeolite was more effective than superphosphate for decreasing the risks of ARGs in chicken manure. Zhang et al. (2018) reported that addition of a natural zeolite into swine manure could further improve ARGs reduction in comparison to the deoxyribonuclease (Dnase) and zero-valent iron addition. Using of natural zeolite-particularly during mesophilic digestion of swine manure-could passivate HMs, which avail the ARGs reduction. By the addition of natural zeolite and zero-valent iron, removal efficiency and the relative abundance of ARGs was enhanced by 138.5% and 33.3%, respectively (Zhang et al., 2018).

Co-composting of OSW with zeolite could provide better conditions for the rapid degradation of OM resulting suitable C/N ratio, high porosity and more active biomass, which can result in a faster maturation and reduced composting time (Turan and Ergun, 2008; Wang et al., 2017c). Addition of zeolite during the composting process could

increase water-holding capacity and aeration and thereby, enhances the humification of OM, assists with nutrient mineralization decomposition, improves efficiency and reduces the duration of composting process (Zhang and Sun, 2015). Water and nutrient retention as a result of zeolite addition (that have been proved by many studies) could increase free air space of the composting materials, inhibit anaerobic condition, increase microbial metabolism and therefore boost the generation of metabolic heat and decomposition of organic material (Zorpas and Loizidou, 2008; Kuran et al., 2014; Zhang and Sun, 2015; Gabhane et al., 2012). The zeolite porous structure may supply a microenvironment that can stabilize enzymes and keep them active throughout the composting process (Venglovsky et al., 2005; Zhang and Sun, 2015). Some studies proved that using zeolite during the composting process decreased the maturation time. The application of zeolite and struvite decreased the maturation time from 7–8 weeks–5 weeks (Chan et al., 2016). Application of 5%, 10% and 15% (w/w) of natural zeolite during the co-composting process of a mixture of water hyacinth, sawdust and cattle manure, increased degradation of OM, thereby enhanced the conversion into the highly stabilized OM. Furthermore, decreased leachability and bioavailability of HMs was observed (Liu et al., 2017). Addition of 10% biochar and 10% zeolite (w/w; dry weight basis) during the composting of pig manure is promoted OM degradation and humification (Wang et al., 2017b). Wang et al. (2017c) reported that the application of 10% zeolite (w/w, dry weight basis) during a sewage sludge composting shortened the maturity period by two weeks compared to the Ca-bentonite and medical stone (both 10% w/w, dry weight basis) treatments (Wang et al., 2017c). It is reported that addition of 30% of zeolite and 1% lime (w/w, dry weight basis) to the composting process of a mixture of biosolids and wheat straw, significantly enhanced OM degradation, humification and enzymatic activities and decreased the maturity period by two weeks (Awasthi et al., 2018). Using zeolite led to accelerate OM degradation and accumulate organic acid in pig manure composting (Mao et al., 2019).

2.3. Effect of zeolites in anaerobic digestion (reducing ammonia gas loss and increasing biogases production)

Addition of food waste and a natural zeolite (clinoptilolite) to an existing up flow anaerobic digester (for a mixture of organic wastes from slaughterhouse as well as chicken, pig and cow manures), improved the production of biogas and reduced the amount of NH₃ in the reactor under warm climate conditions (Loizia et al., 2019). The addition of zeolite decreased the NH₃ losses and increased the CH₄ production during the batch thermophilic anaerobic digestion of cattle manure (Borja et al., 1996). Trapping of CH₄ in the anaerobic digester for energy purposes could meaningfully decrease the GHGs emission from manure (Sommer et al., 2004). Zeolite with its unique physical and chemical properties for microorganism adhesion has also been suggested as an ion exchanger for the adsorption of NH₃ in anaerobic digestion because of its high adsorptive capacity. Application of zeolite boosted biogas production during the anaerobic digestion (Montalvo et al., 2012). Wijesinghe (2017) reported that the application of zeolite in the anaerobic digestion process can be considered as an efficient way of increasing CH₄ production by removing potassium inhibition and NH₃ inhibition during the swine composting. Addition of various dosage of zeolite (10–100 g/L) into the swine manure digesters showed that all digesters containing zeolite made more biogas and CH₄. The result showed that a natural zeolite application rate of 40 g/L resulted in the highest increase (29%) in total CH₄ yield compared to the control. Addition of zeolites at a dose of 100 g/L decreased the total ammoniacal N concentration by 50% (Wijesinghe, 2017). Co-composting of a mixture of food waste and 2.5–5% (w/w) of clinoptilolite increased CH₄ production and decreased CO₂ and NH₃ levels. This is very important because stabilized sewage sludge could be easily composted without any toxicity associated with NH₃ release (Loizia et al., 2019).

2.4. Effect of zeolite on heavy metals (HMs) content of compost

The content, behavior, and significance of HMs (e.g. Cd, Cr, Cu, Zn, Pb, Hg) and toxic metalloids (e.g. As) of OSW composting products are imperative from two potentially conflicting traits of environmental legislation regarding: (a) defining end-of-waste criteria and enhancing recycling of composted residuals and (b) protecting soil quality by preventing contamination (Smith, 2009). The long-term use of OSW compost especially sewage sludge with a background of HMs may enhance the amount and accumulation of the HMs in soil even though the HMs concentration in compost is lower than the maximum allowable concentration defined by regulatory bodies (Singh and Kalamdhad, 2014b). While the HMs in OSW cannot be removed through composting process however, the HMs bioavailability, which is the main sources of soil pollution can be altered (Wang et al., 2018b). The HMs bioavailability, depends on various extractable fractions in reference to the total metal concentration (Nair et al., 2008). Zeolites can readily uptake almost all of the HMs that are bound to the carbonate and the exchangeable fractions with a selectivity of: Cu > Cr > Fe > Ni > Mn > Pb > Zn (Singh and Kalamdhad, 2012; Zorpas et al., 2000). Clinoptilolite possesses the ability to exchange its alkaline and alkaline earth cations with HMs and other cations (e.g. NH₄⁺) in the surrounding environment. By increasing the percentage of zeolite in compost, water solubility and DTPA and toxicity characteristic leaching procedure extractability of HMs can be decreased while the concentration of potassium, calcium and sodium might be increased (Singh et al., 2016). During composting processes, the presence of metals in the exchangeable form may increase by the breakdown of organic matter, in which they can be adsorbed and immobilize by zeolites through ion exchange mechanism (Stylianou et al., 2008).

As summarized in Table 3, many researchers studied the effect of zeolites in improvement of composting process by reducing the mobility of the HMs. This can be attributed to the cation exchange of porous zeolitic materials. In some studies, researchers used high dosages of zeolites to reduce the bioavailability of HMs. While the results were promising however, very high dosage of zeolite-as an inorganic compound-could negatively imbalance the OM content of final product. Furthermore, adding of a very high percentage of a zeolitic aluminosilicate will eventually change the soil composition in long term. We believe that the effect of applying composts with very high percentage of zeolite to soil, needs to be studied in more depth to evaluate their long-term impact on the soil quality particularly OM content of soil. For example by adding 25–30% of zeolite during the sewage sludge composting process, up to 100% of Cd, 28–45% of Cu, 41–47% of Fe, 10–15% of Cr, 9–24% of Mn, 40–46% of Zn and 50–55% of Ni and Pb were immobilized (Zorpas et al., 2000, 1999). In another study, 10–25% of clinoptilolite (dry weight basis) with particle size of <0.16mm-4 mm was applied for removal of HMs from sewage sludge. Significant removal of HMs was observed by using 25% of zeolite with a particle size of

Table 3
Effect of zeolite on heavy metals of compost.

Type/source of composted material	Country	Reference
Sewage sludge	Greece	(Zorpas et al., 2000, 1999)
Sewage sludge	Greece	Zorpas et al. (2002)
Sewage sludge	Greece	Zorpas (2014)
Sewage sludge	Taiwan	Chiang et al. (2007)
Sewage sludge	Greece	Stylianou et al. (2008)
Sewage sludge	Greece	Zorpas (2011)
Sewage sludge	Cyprus	(Zorpas et al., 2008; Zorpas and Loizidou, 2008)
Sludge-straw	Spain	Villasenor et al. (2011)
Green waste (Water hyacinth, cattle manure (cow dung) and sawdust)	India	Singh and Kalamdhad (2014a)
Co-composting of paddy husk and chicken slurry	Malaysia	Latifah et al. (2015)
Dewatered fresh sewage sludge	China	Awasthi et al. (2018)

3.3–4.0 mm. With decreasing of the zeolite particle size, lower uptake of metals was observed. They attributed the observation to possible pore clogging and structural damage of zeolites with smaller particle sizes (Zorpas et al., 2002). Their conclusion cannot be justified because technically speaking zeolites with smaller particles sizes should exhibit larger surface area and higher number of accessible exchange sites, therefore, faster cation exchange reaction and larger experimental CEC. It is noteworthy that theoretical CEC is a characteristic property of each zeolitic compound that will not change by changing the particle size. Zorpas (2011) reported that the selectivity of clinoptilolite to HMs in sewage sludge compost can be affected by contact time and temperature. A number of experiments were carried out using 25% w/w clinoptilolite (2.5–2.7 mm) and 75% w/w sewage sludge under different reaction conditions in order to study the effect of composting temperature (20, 40 and 60 °C) and contact time (1–30 d) on the uptake of HMs by clinoptilolite. The selectivity series for the removal of HMs was different from temperature to temperature and from day to day. The optimum result was obtained after 30 d of composting at 60 ± 2 °C (Zorpas, 2011). Application of 10%, and 20% of natural zeolite (w/w wet basis) and lime can meaningfully reduce the amount of DTPA-extractable Pb, Zn, Ni, and Cu cations in the matured compost of sewage sludge. This observation is attributed to the higher ion exchange capacity or alkalinity of the final compost because of its zeolite content (Chiang et al., 2007). Total concentration and water-extractable metals (Cu, Cr, Zn, Ni and Mn), EC and C/N ratio in a mature sewage sludge compost were reduced by the addition of 20% (dry weight basis) of natural clinoptilolite (Stylianou et al., 2008). Zeolite (up to 30% and particle size of 2.5–2.7 mm) can trap a significant amount of mobile HMs (e.g. the carbonate and the exchangeable fraction) from sewage sludge compost. It is noteworthy that significant amount of HMs that cannot be adsorbed by zeolite are associated with the residual fraction that are known as inert forms (Zorpas et al., 2008; Zorpas and Loizidou, 2008). In another study, 10–40% (w/w, wet weight basis) of two clinoptilolite from different sources (*with trade names of Klinolith and Zeocat*) successfully removed up to 100% of Ni, Cr, Pb, and up to 60% of Cu, Zn, and Hg cations from a composted product of mixture of sludge and straw. Zeocat exhibited a higher removal efficiency, which was enhanced by increasing of the zeolite dosage. Singh and Kalamdhad (2014a) showed that the toxicity of HMs in a green waste mixture compost (i.e. water hyacinth, cattle manure and sawdust) is associated with its bioavailable fractions rather than the total metal concentration. The addition of 5%, 10% and 15% of natural zeolite (w/w wet basis) significantly decreased the bioavailable fractions of HMs during rotary drum composting of a water hyacinth (Singh and Kalamdhad, 2014a). Zorpas (2014) used 25% w/w of natural zeolite (clinoptilolite) in the composting process of sewage sludge for several times to define the recycle index (RI) and to find out which mathematical model can describe this phenomenon. They reported that under particular circumstances, the same amount of natural zeolites can be reused for 22 times (RI = 22), which makes the whole process more sustainable and less expensive. The HMs content of reused zeolite exhibited a direct relation with the numbers of usage. The results from the mathematical modelling supported experimental data (Zorpas, 2014). While reusing of composting additives might be a good idea however, it is noteworthy that mechanical separation of zeolitic particulate from a compost mixture is not an easy process to implement at larger scale productions. Clinoptilolite used in co-composting of paddy husk and chicken manure slurry decreased the accumulation of HMs due to high specific surface area and CEC of the zeolite (Latifah et al., 2015). Natural zeolite (10%, 15% and 30% w/w; dry weight basis) was applied to improve the quality of composting product of a mixture of biosolids and wheat straw. While the higher dosage of zeolite (i.e. 30%) plus 1% lime treatment significantly decreased the bioavailability of Cu and Zn cations and the humification process however, modification of compost with 10% zeolite and 1% lime was suggested as an economically feasible practice for co-composting of biosolids (Awasthi et al., 2018).

3. Effect of compost containing zeolites in agriculture

Most of the composting products exhibit a relatively high electrical conductivity (EC), limited amount of nutrients (mainly N losses) because of NH₃ emission during the composting process and leaching other nutrients such as phosphate and potassium, low WHC and low level of organic matters. Therefore, in many cases, OSW composting products might not be able to provide enough nutrients to soil needed for growing different crops. Because of unique physiochemical characteristics of natural zeolites, including but not limited to: high CEC and high WHC, they can be used as additives to the composting processes for addressing some of the shortcomings/drawbacks of application of traditional composting products to farmlands (Waqas et al., 2018). When HMs contaminated compost applied to the soil, plants HMs uptake and successive accumulation along the food chain is a probable hazard to animal and human health (Wong and Selvam, 2006).

The utilization of zeolite-modified composting products for agricultural purposes has shown numerous agronomic, environmental and economic benefits (Table 4). Organo-zeolitic-soil systems offer an opportunity to re-vegetate lands the made barren because of HMs pollution. Lands revegetation will reduce soil erosion and therefore releasing of HMs contaminants and nutrients to the water bodies will be reduced (Leggo, 2006). Addition of synthetic zeolite P for improving the quality of sewage sludge compost significantly decreased the soil metal mobility and soil-plant transfer (Nissen et al., 2000). The effect of various combinations of green waste and sewage sludge (1:1 w/w) compost and clinoptilolite zeolite (up to 20% w/w) on a contaminated soil containing high levels of arsenic (34470 mg kg⁻¹) is studied. Experimental data showed that 15% compost with 5% zeolite is efficient in decreasing plant arsenic uptake and establishing revegetation on the contaminated soil (Gadepalle et al., 2008). Leggo (2006) developed a bio-fertilizer by mixing clinoptilolite zeolitic tuff (0.5–2.0 mm) with poultry manure, in a 1:2 ratio (v/v). The zeolitic component of the soil system supports biofilm formation, which can be associated to the higher rate of plant growth on the substrates containing zeolite. Similar trends are found for plants growing in clean and metal-polluted soils (Leggo, 2006). Joghhan et al. (2010) reported that using composted cattle manure modified with zeolite had a positive effect on nutrition residue and soil fertility of a wheat farm (Joghhan et al., 2010). Gholamhoseini et al. (2013) indicated that the application of a cattle manure compost modified with natural zeolite in a sandy soil improved soil property, reduced the N leaching, increased the plant-available N and as a result, increased N usage efficiency and the yield of sunflower seed. In addition, the soil amended with manure and zeolite exhibited a higher irrigation water productivity that explained by improved plant growth and water retention capacity of zeolite. Application of cattle manure containing zeolite could be considered as a feasible approach toward sustainable agricultural by reducing the usage of chemical fertilizers (Gholamhoseini et al., 2013). A greenhouse experiments ascertained that using a compost containing 12% biochar and 15% zeolite (w/w; dry weight) increased the dry weight biomass of Chinese cabbage (*Brassica rapa chinensis* L.) which

Table 4
Effect of compost containing zeolite on plant growth.

type of composted material	Country	Reference
Sewage sludge	United Kingdom	Nissen et al. (2000)
A combination of composted green waste and sewage sludge	United Kingdom	Gadepalle et al. (2008)
Poultry manure	UK	Leggo (2006)
Cattle manure	Iran	Joghhan et al. (2010)
Manure	Iran	Gholamhoseini et al. (2013)
Dewatered fresh sewage sludge	China	Awasthi et al. (2017a)
Municipal solid waste	Saudi Arabia	Waqas et al. (2018)
Municipal organic solid waste	Iran	(Taheri Soudejani et al., 2018, 2019b)

was attributed to the increased availability of macro-nutrients and reduced bioavailability of HMs in soil and plants (Awasthi et al., 2017a). Addition of natural zeolites and biochar are very popular technique studied by many researchers for improving the quality of a food waste. A technical report by Wagas et al. (2018) has suggested that optimization and process improvement in food waste compost facilities could benefit the Kingdom of Saudi Arabia economy with a total net savings of about US \$70.72 million per year (Wagas et al., 2018). Taheri Soudejani et al. (2018, 2019b) have reported that adding a compost containing natural and Mg- modified zeolite to soil can increase the shoot dry weight of corn by 40% and 56%, respectively. The amount of total NO_3 leached from compost containing natural and Mg- modified zeolite treatments was decreased by 21.0% and 28.9%, respectively. Mg- modified zeolite was more effective than natural one for retention of water in soil, in which the moisture content in the surface layer of soil was increased by 12.6%. Using clinoptilolite zeolite and particularly its Mg-modified forms during composting process decreased HMs concentration in mature compost, subsequently in the roots, stalks, and leaves of corn (Taheri Soudejani et al., 2018, 2019b).

Application of a mixture of compost and zeolite in pepper, oats and eggplant cultivation increased the final product yield. The zeolite could retain the HMs and reduced their bioavailability resulting lower level of HMs in the crops (Zorpas, 2008). They evaluated the phytotoxicity and the humics content of the final product. They concluded that a substrate made of 25% clinoptilolite and 75% Sewage Sludge (v/v) was non-phytotoxic after 80 days of maturity. The germination index (GI) was 78, 75 and 72 for oats, eggplant and pepper seeds, respectively. When $0 < \text{GI} < 26$, a substrate will be classified as very phytotoxic, if $27 < \text{GI} < 66$, a substrate is categorized as a phytotoxic media. A substrate with a $67 < \text{GI} < 100$ is characterized as non-phytotoxic and finally a substrate with a $\text{GI} > 101$ are is phytonutrients. Zeolite can increase the porosity of soil that positively impacts the cultivation. They reported that total humics of the treated soil was lower due to the lower concentrations of lignin and cellulose in the initial sample of sewage sludge (Zorpas, 2008). Application of clinoptilolite improved compost quality produced from pistachio biowaste (Doula et al., 2018). It was found that 5% w/w of natural zeolite (clinoptilolite) in the feed-stock mixture improved the quality of the final composting product. Moreover, properties of the zeolite-modified compost were in compliance with the European standards for the safe application of composts and other organic materials as soil amenders. They concluded that zeolite can be used in modified composting processed and the final products can be used in farmlands for plant growth and land restoration purposes.

Soils that receive olive mill wastes (OMW) are eventually become overloaded with OM of unknown and insufficient quality as well as inorganic nutrients and polyphenols. Olive oil production is considered to be one of the oldest agricultural processing particularly in the Mediterranean region (Zorpas and Zzia, 2008). They typically produced using one of the following extraction processes: a) traditional discontinuous press process; b) two-phase and c) three-phase centrifugal extraction technique. Through the production process, several waste streams and by-products such as olive wood and leaves, cake, kernel, and olive mill wastewater are generated. Natural clinoptilolite zeolite was used as soil additive to investigate its effectiveness in protecting and improving the quality of soils that received surface disposal of OMW and to study its effect on reducing nutrients washout from the degraded soils (Doula et al., 2019). Soil properties are strongly impacted by the direct disposal of OMW to farmlands. EC of such soil can be very high (up to 6.0 mS cm^{-1}) even 12 years after disposal of OMW. It is reported that addition of natural clinoptilolite -as a soil amender-to the degraded soils have a positive impact on soil salinity, which is a major degradation and abiotic factor limiting crop production (Zorpas et al., 2010). Using 5% Ca-rich clinoptilolite as soil amendment showed positive impact on the quality of treated soil (Al-Busaidi et al., 2008).

It can be concluded that the application of natural zeolites and their modified forms to improve composting process could positively impact

salinity stress, nutrient balance in soil, and enhances water and salt holding capacity. However, to the best of our knowledge, there is not any scientific report on potential positive or negative cumulative effects of long term applications of zeolites to the soil. Technically speaking, zeolitic aluminosilicates have a very strong and robust structure that can remain in soil for a very long time and eventually change its texture. Therefore, it is noteworthy that inappropriate addition of zeolite to compost at very high dosage (as it is reported by many researchers), might imbalance compost OM content that eventually might impact the soil texture negatively. Therefore, more in-depth studies are necessary to evaluate longer term impacts of applying zeolitic aluminosilicates to the agricultural lands directly or through composting products modified with zeolites.

4. Conclusion

Environmental pollution such as odorous gaseous emissions generated during the composting process, is considered as one of the major environmental impacts associated with traditional composting processes. Nitrogen as a plant macro nutrient, if released in gaseous form (NH_3), will have adverse effects on human health and vegetation. It can be converted to N_2O , which is a powerful GHGs. The major part of ammonia produced while composting, is released as NH_3 gas, leading to environmental pollution and a reduction in the N content of the final composting product. Furthermore, some N can be lost as NH_4^+ into the leachate of the composting process, particularly in windrow composting practices. In addition, the presence of HMs in compost is another environmental detriment for the widespread use of compost in the agriculture industry. Natural zeolites with unique physio-chemical characteristics and remarkable selectivity for capturing gaseous NH_3 , NH_4^+ and HMs contaminants are proven to be an inexpensive, yet environmentally friendly candidates for addressing some of the shortcomings of traditional composting processes. In order to select a proper type of zeolite for composting applications, different properties of the zeolite including: cation exchange capacity and selectivity (for HMs and NH_4^+), adsorption capacity (for NH_3 and other malodorous molecules) and WHC should be taken into consideration.

In conclusion, some of the major financial and environmental benefits of modifying traditional compost processes with zeolites can be summarized as:

- Decreasing the environmental impact of composting process via controlling (reducing) release different gaseous molecules such as NH_3 to the atmosphere.
- Elimination or size reduction of the NH_3 -scrubbing unit that uses sulfuric acid and produces large amounts of secondary liquid waste.
- Zeolite addition contributes to microbial activities and promotes compost decomposition.
- The produced zeolite-modified compost is a value-added product with higher nutrient content that can be tailored for using in different agricultural, horticultural and soil amendment applications.
- Natural zeolite (unmodified form) are mainly capable of adsorbing (trapping) N compounds (e.g. NH_4^+ and NH_3) and HMs cations, however some of the modified zeolites (e.g. Mg-form) can be used for retaining of both cationic and anionic species including phosphate as a nutrient.
- Zeolite could trap (and fix) unwanted HMs cations in composting products by reducing their bioavailability to the crops.
- While natural clinoptilolite (mainly because of its abundant occurrence worldwide) is the most studied zeolite species in composting process, however other natural zeolites and some of the synthetic zeolites showed very promising properties for compost modification as well.
- It is obvious that more research is needed to optimize the process of zeolite addition to compost in order to obtain the highest value-

added product (e.g. the stage of addition, optimized dosage, different modified zeolites, method of addition, optimize particle size, etc.). Furthermore, despite all the proven benefits of using zeolite to improve traditional composting processes and products, because of its inorganic and stable structure, zeolite-like other tectosilicates will remain in the soil for a very long time, therefore, it may change the soil texture and properties. While most of zeolite properties are beneficial to agricultural soils and in fact it has been used as soil amender for several remediation purposes, more in-depth studies are necessary to evaluate the long-term cumulative effect of addition of zeolitic minerals to agricultural lands.

- i Researchers are applying a very wide range of zeolite dosage (e.g. from 1% to 60%) to modify composting processes. Application of very large dosages of natural zeolite should be considered cautiously because zeolites are inorganic aluminosilicate minerals that can withstand harsh environmental conditions without significant structural change. Therefore, long term application of zeolite may have some unexpected and unknown negative impacts on the soil quality.
- j Therefore, for a more comprehensive and in-depth evaluation of modified co-composting processes of organic solid wastes with mineral additives, more interdisciplinary researches should be conducted. It seems proactive collaboration between different disciplines from geology to chemistry, from soil science to environmental science and engineering, from toxicology to plan biology and from chemical engineering to agronomy is needed to study potential long term/cumulative impacts of adding inorganic additives such as zeolites and other aluminosilicates through modified composting products to the agricultural soil.

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