Journal of Agricultural and Marine Sciences 2022, 27(1): 38–61
DOI: 10.53541/jams.vol27iss1pp38-61
Received 02 March 2021
Accepted 01 Sep 2021

REVIEW ARTICLE

A 25-Year History of the use of Organic Soil Amendments in Oman: A review

Rhonda Janke*[1], Daniel Blackburn[2], Mumtaz Khan[1], Ahmed Al Busaidi[2], Waleed Al Busaidi[1], Ali Al Hinai[1] and Mushtaque Ahmed[2]

إستخدام المحسنات العضوية للتربة في عمان خلال الـ٢٥ عاما الماضية: مراجعة

روندا جانكي, دانيل بلاكبيرن, ممتاز حان, أحمد البوسعيدي, وليد البوسعيدي, علي الهنائي, مشتاق أحمد

ABSTRACT. Organic soil amendments have been used in Oman since prehistoric agriculture began and are still being used today. Recently, interest in certified organic farming, and the use of organic soil amendments to enhance soil quality has motivated more research on traditional and new diverse soil amendment products. In addition, the arid climate of Oman combined with sandy soils benefit from non-traditional soil amendments and nutrient sources, such as treated human waste and wastewater. These two are not allowed in certified organic farming but offer sustainable solutions to building soil health for non-certified crops. This review will cover studies of soil quality in Oman related to the comparison of these various amendments, including manures, composts, organic mulch materials, biochar, ash, and others. In general, most of these amendments improve the soil by adding organic carbon, increasing the water holding capacity, improving infiltration rate, and stimulating or providing habitat and food sources for diverse soil microbiological communities. Some amendments can also help crops overcome some of the stresses of agriculture in Oman, such as soil salinity, heat and drought. Most also provide macro and micronutrients for crop growth. Some anti-quality factors may be present however, such as a high carbon to nitrogen ratio in some mulches, or high heavy metal content, human pathogens, and pharmaceutical residues in treated waste or wastewater. Biochar may have a positive or negative effect on soil microbes, depending on the source material and temperature of combustion can result in byproducts that inhibit microbes. The value of soil microorganisms has been shown in organic cropping systems, and several new species have been discovered in Oman. Some of these provide possibilities for biocontrol of pathogens, and increased salt tolerance in crops like tomato. Though much valuable research has been done in Oman and the rest of the world, there is much left to be done to determine the effects of these organic amendments over the long term, and also the interactions among various amendments, soil conditions, soil microbes, and on crops grown with different irrigation methods and cropping systems.

KEYWORDS: Organic farming, soil quality, microbial diversity, biochar, soil fertility.

الملخص: تم استخدام المحسنات العضوية للتربة في عمان منذ أن بدأت الزراعة في عصور ما قبل التاريخ وما زالت تستخدم حتى اليوم. في الآونة الأخيرة، أدى الإهتمام بالزراعة العضوية المعتمدة وإستخدام المحسنات العضوية من أجل تحسين جودة التربة إلى تحفيز المزيد من البحث حول المنتجات المحسنة في التربة التقليدية والجديدة المتنوعة. بالإضافة إلى ذلك ، فإن المناخ الجاف في عمان مع التربة الرملية أدى الى الإستفادة من محسنات التربة غير التقليدية ومصادر المغذيات ، مثل النفايات البشرية المعالجة ومياه الصرف الصحي. لا يُسمح بهذين الاثنين في الزراعة العضوية المعتمدة ولكنهما يقدمان حلولًا مستدامة لصحة التربة للمحاصيل الغير معتمدة في الزراعة العضوية. ستغطي هذه المراجعة دراسات جودة التربة في عُمان فيما يتعلق بمقارنة هذه المحسنات المختلفة، بما في ذلك السماد الطبيعي، السماد العضوي، مواد الغطاء العضوية، الفحم الحيوي، الرماد، وغيرها. بشكل عام، تعمل معظم هذه المحسنات على تحسين التربة عن طريق إضافة الكربون العضوي، زيادة القدرة على الاحتفاظ بالمياه، تحسين معدل الترشيح، تحفيز أو توفير مصادر الغذاء و بيئة للمجتمعات الكائنات الدقيقة للتربة المتنوعة .كما يمكن لبعض المحسنات أن تساعد المحاصيل في التغلب على بعض ضغوط الزراعة في عمان، مثل ملوحة التربة والحرارة والجفاف. أيضًا توفر معظمها العناصر الغذائية الكبرى والصغرى لنمو المحاصيل. ومع ذلك، قد توجد بعض العوامل المؤثرة على الجودة، مثل ارتفاع نسبة الكربون إلى النيتروجين في بعض الأغطية، أو المحتوى العالي من المعادن الثقيلة، مسببات الأمراض البشرية، ومخلفات الأدوية في النفايات المعالجة أو مياه الصرف الصحي. قد يكون للفحم الحيوي تأثير إيجابي أو سلبي على ميكروبات التربة، اعتمادًا على مصدر المادة ودرجة حرارة الاحتراق وعليه يمكن أن يؤدي إلى تشكل منتجات جانبية تمنع الميكروبات. تم توضيح قيمة الكائنات الحية الدقيقة في التربة في أنظمة المحاصيل العضوية، كما تم اكتشاف العديد من الأنواع الجديدة في عمان. بعضها يكون قادر على مكافحة مسببات الأمراض حيويا، وزيادة تحمل الملوحة في المحاصيل مثل الطماطم. على الرغم من إجراء الكثير من الأبحاث القيمة في عُمان وبقية العالم، إلا أنه لا يزال هناك الكثيرمن ما يتعين القيام به لتحديد آثار هذه المحسنات العضوية على المدى الطويل، وكذلك نتائج التفاعلات بين المحسنات المختلفة، وحال التربة، وما تحتويه من ميكروبات، وعلى المحاصيل المزروعة بطرق الري وأنظمة الزراعة المختلفة.

الكلمات المفتاحية: الزراعة العضوية، جودة التربة، التنوع الميكروبي، الفحم الحيوي، خصوبة التربة.

Introduction

Since the beginning of agriculture, humans have found ways to enrich the soil, and thus benefit from healthier crops and better yields. (Price and Gebauer, 1996). With the advent of processed fertilizer production, the manufacture and mining and concentration of the minerals required by plants has become more convenient, but not without cost to soil quality, if soil carbon enrichment is neglected.

Different farming systems around the world use various methods and combinations of materials to add this soil carbon, including the addition of livestock manures, composts, green manure legume cover crops, adding

Rhonda Janke*[1] (✉) rhonda@squ.edu.om, [1]Department of Plant Sciences, [2]Department of Soil, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, PO Box 34, Al Koud, 123 Muscat, Oman.

mulch to the surface of the soil, by leaving the residue from high biomass crops, and rotation between annual and perennial crops. Oman has a unique combination of climate, sandy soils, and limited fresh water for agriculture. Both perennial and annual crops are grown, in multi-layered mixtures on traditional farms, and monocultures with high tillage inputs on more recent contemporary farms (Gaube and Gangler, 2012). There are trade-offs among various cropping systems and methods; some enhance soil quality, and some deplete it, jeopardizing future agriculture on some sites.

The purpose of this review is to summarize what we know about soil quality in Oman, both from research conducted within the country, and to combine it with what we know about similar research around the world. The review will start with a brief summary of the current situation in Oman, some historical aspects, and the relationship among farming practices, soil quality, water quality and quantity, and other contextual factors.

Then we summarize commonly used soil fertility amendments, and then move on to recent research on novel, less traditional amendments such as biochar. The role of microbial activity and diversity within these cropping systems are discussed, with special emphasis on studies for the future related to soil organic matter and soil quality, as well as the way that bacteria and fungi can protect plants from biotic and abiotic stresses. In addition, new ways of recycling human waste, as sludge, compost, and wastewater are considered as partial solutions to the need to improve soil quality and conserve water resources in an arid climate.

Methodology

The goal of this literature review was to summarize all the research that could be located in the topic areas just described for Oman. The 25 year time-frame corresponds to the 25 year history of the Journal of Agricultural and Marine Sciences at Sultan Qaboos University. The authors of this paper have all been publishing in their respective areas of expertise and used the multiple scholarly data-bases available through the library system, the internet, and also harder to locate published data in Ministry of Agriculture annual reports and surveys. In some cases, graduate student thesis and dissertation data was cited if the work has not been yet submitted to a journal. The Oman data was then put into context by also citing well-known, recent, or review papers from world-wide refereed journals.

This review is not a quantitative summary, using only certain key-words, but qualitative; sifting through what is known, and what is not yet known about soils in Oman. Through this iterative process of comparing what is known in Oman and studies in other countries, gaps in our understanding and fruitful areas for future research could be identified.

History of Farming, the Soil Survey, and Irrigation Systems in Oman - Context

Oman has a long history and tradition of agriculture, with some of the irrigation systems, or aflaj, dating back 3000 years. "This oasis culture, formed thousands of years ago, represents a symbiotic unity of lifestyle and environment" (Gaube and Gangler, 2012). Traditional farming systems are often planted with multiple species of crops in the same area, and contain more biological diversity, including both weeds and also medicinal plants, than modern monoculture date palm plantations (Al Yahyai and Al Hashmi, 2017).

Date palm and pomegranate are traditional perennial fruit crops (Al Said et al., 2013; Al-Yahyai and Khan, 2015), along with annual crops like wheat, barley and garlic, and forages such as alfalfa. At least 30 different crops have landraces and local varieties that have been recognized and are being conserved in Oman (Al-Lawati et al., 2017). In an example traditional oasis farming communities, 66 different crop species are under cultivation in the mountain village, Balad Seet (Gaube and Gangler, 2012), including traditional crops, as well as more recently introduced species. About half of the cropped area was planted to alfalfa and barley, to be used as forage crops for ruminants. The manure from the approximately 200 goats or sheep, and up to 30 cattle were applied to the crops, both with and without additional chemical fertilizers, or sometimes fertilizer alone was applied. Rates of up to 380 kg N, 30 kg P, and 400 kg K per ha, were applied and varied across crops and seasons (Gaube and Gangler, 2012).

A soil survey of Oman was completed in 1990 (MAP, 1990) and classified the soils according to international soil taxonomy standards into 61 different mapping units, belonging to 3 soil orders: Entisols, Inceptisols, and Aridisols (Cookson, 1996). Entisols are soils that show little profile development or diagnostic horizons, and are basically unaltered parent material. Inceptisols are recently formed soils, show more horizon development than Entisols, but do not have any accumulation of clays, iron oxide, aluminum oxide, or organic matter. Aridisols form in arid and semi-arid climates, and make up about one third of the earth's land surface. In addition to the presence of rocks and steep slopes, the soils of Oman have other limitations for agriculture such as gypsum accumulation, calcium carbonate accumulation, and soil and water salinity. About 2,000,000 ha of the total land area is categorized as Class 1 or 2, which is highly/moderately, or marginally suitable for agriculture, which is about 6.5% of all soils. Only 800,000 ha are in the Class 1 category, or only 2.59% of the soils of Oman (Cookson, 1996; MAF, 1990).

Between 1988 and 1997, more detailed soil surveys of the agricultural regions were carried out in the Salalah region/Governate of Dhofar (MAF, 1992), in South Al Batinah (MAF, 1993) and in North Al Batinah, in 3 ar-

Table 1. Land area in agriculture, cropped land, and percent ag land treated with pesticide, chemical fertilizer, non-processed organic fertilizer and processed organic fertilizer (MAF 2015).

Governate	total area in ha	total agricultural land area (ha)	percent of total area in agricultural land	Cropped Area (ha)	percent of total area in cropped land	percent of ag area that is cropped	# holdings (with land)	percent of total ag area treated with pesticide	percent of total ag area treated with chemical fertilizer	percent of total ag area treated with non-processed organic fertilizer (manures)	percent of total ag area treated with processed organic fertilizer (compost)
Al Batina North	790,000	35,750	4.53%	24,875	3.15%	69.6%	21,777	49.5%	71.9%	83.9%	47.9%
Al Batinah South	532,000	20,574	3.87%	10,838	2.04%	52.7%	19,532	47.9%	63.8%	83.6%	56.0%
Ad Dakhiliyah	3,180,000	19,208	0.60%	7,547	0.24%	39.3%	31,293	70.5%	64.7%	92.2%	39.2%
Dhofar	9,910,000	27,687	0.28%	7,467	0.08%	27.0%	11,498	80.7%	53.2%	92.3%	49.1%
Ash Sharqiyah North	2,110,000	11,560	0.55%	5,687	0.27%	49.2%	24,284	49.0%	49.4%	93.0%	46.4%
Adh Dahirah	3,590,000	13,984	0.39%	4,963	0.14%	35.5%	15,406	56.9%	56.7%	88.8%	38.1%
Ash Sharquiyah South	1,200,000	6,387	0.53%	3,280	0.27%	51.4%	12,861	43.9%	40.7%	92.5%	36.8%
Al Buraimi	746,000	6,772	0.91%	3,154	0.42%	46.6%	4,504	66.6%	50.5%	92.5%	23.7%
Muscat	380,000	4,853	1.28%	2,601	0.68%	53.6%	8,354	55.0%	50.2%	92.8%	38.3%
Musandam	162,000	1,362	0.84%	911	0.56%	66.9%	3,871	41.8%	18.4%	68.9%	11.4%
Al Wusta	8,250,000	969	0.01%	163	0.00%	16.9%	630	85.6%	27.6%	93.1%	37.2%
Total	30,850,000	149,105	0.48%	71,488	0.23%	47.9%	154,010	59.3%	59.4%	88.6%	44.8%

eas; Sohar, Liwa and Shinas (MAF, 1997a; MAF 1997b; MAF 1997c). The Salalah detailed soil survey covered an area of about 4,200 ha (about 0.04% of the total land area of Dhofar). From this study area about 60 percent of the topsoil was coarse loamy (loam or sandy loam) and about 7 percent was fine loamy (heavy loam or sandy clay loam). Available water holding capacity was conducted and found that about 56 percent was high or moderate, and about 42 percent were low and very low. Infiltration rate of the study area was generally low to moderately low (71%), moderate (13%) and moderately high to very high (14%). Soil pH was generally slightly to moderately alkaline. Most soils of the study area were none to slightly saline (83%), moderately saline (14%) and strongly saline (2.5%) as measured by electrical conductivity (EC). The average topsoil cations exchange capacity (CEC) was low. Calcium followed by magnesium were the main cations while potassium content was moderate. Organic matter was higher than in other areas in the Sultanate but it was classified as low by international standards. The average of available phosphorus was moderate to high (9.6 ppm) (MAF, 1992).

The soil survey of South Al-Batinah was conducted between 1988 and 1992. It covered an area of 65,900 ha of Willayats of Barka, Masanaa, and Suwayq. About 3,200 soil samples were collected for general chemical and physical analysis. Infiltration and permeability tests were also conducted by using of double rings infiltrometers. The soils of the study area developed mostly on alluvium derived from the Hajar mountains. In the study area the topsoil, it was mostly coarse textured; about 80% sandy or coarse loamy, and 20% fine textured. The infiltration rate for 60% of soils was moderately to very rapid, and only about 9 % had slow permeability. The average topsoil calcium carbonate content was higher in Barka compared to Masanaa and Suwayq. The soil pH was generally moderately to strongly alkaline. In addition, about 50 % of the soils of the area were not saline. However, 30 % were strongly affected by salinity, due to inadequate salt leaching and saline irrigation water. The average topsoil cation exchange capacity was generally low. Calcium followed by magnesium were the main cations in the soil while potassium content was moderate. In addition, soil organic matter and nitrogen content were low while available phosphorus was generally moderate (MAF, 1993).

In the North Al-Batinah soil survey, the soil surveys for Sohar, Shinas and Liwas were conducted between 1995 and 1997. Soil samples were analyzed for pH, EC, and carbonate content, CEC and extractable bases, organic carbon and available phosphorus contents on the topsoil samples. In addition, triplicate double-ring infiltration tests was carried out (MAF, 1997a; MAF, 1997b; MAF, 1997c). Results were similar to the South Al Batinah study. Salinity, partly due to seawater intrusion, is a limitation to much of the coastal farmlands in both North and South Al Batinah, with an estimate that overall, 52% of the soils in these Governates are affected to some degree by salinity, with an EC level greater than 3.0 dSM^{-1} (Hussain, 2005).

The most recent agricultural survey (MAF 2015) shows that at present, only 0.48% of the land of Oman is in agriculture, and that only 0.23% is cropped (Table 1). This is quite a bit lower than the 6.5%, or even the 2.59% of soils that are suitable for farming according to the soil survey. The difference between cropped and agricultural lands is that some land is used for buildings, grazing, and other livestock holdings or fallow. The other limitation to agriculture in Oman besides soil suitability is the availability of water, which is why these numbers are fall below the potential based on soil suitability.

Oman is categorized as a country of "extreme water scarcity" by the FAO, and yet it has a thriving agricultural sector, with an estimated 50% self-sufficiency rate for vegetable crops, and a 70% self-sufficiency rate for fruit (Mbaga, 2014). However, this production comes at the expense of water use, which was estimated in a 1999 study to exceed sustainable re-charge by 25% (National Water Resources Master Plan, 1999). A follow-up study in 2013 also confirmed that Oman continues to have a net water deficit of 315 Mm3 per year (Ministry of Regional Municipalities and Water Resource, 2013).

Both traditional aflaj methods of irrigation (usually flood) and drip irrigation from wells are used, but in different ratios in different parts of Oman (Figure 1). Of the total water used for agriculture of 1546 Mm3, about two-thirds, or 1060 Mm^3 are groundwater extracted by wells/pumping, and 486 Mm^3 flow through the aflaj systems (Ministry of Regional Municipalities and Water Resource, 2013). Wells are the primary irrigation sources for both North and South Al Batina, which account for 50% of all of the cropped land in Oman. In these two Governates, agriculture makes up 2 to 3% of the total land area. Ad Dakhiliyah and Dhofar are 3rd and 4th place in number of cropped ha, but only have 0.24 and 0.08% of their total land area in crops respectively (Table 1). Farms in the Governate of Ad Dakhiliyah have access to a mix of aflaj and groundwater/wells (Figure 1), while in Dhofar, the only source is groundwater. Al Wusta has the lowest amount of land in agricultural production (Table 1), even though some soils are suitable, due to the lack of any easily accessible water source (Figure 1).

Moving towards drip irrigation on many vegetable farms has improved water use efficiency (WUE), but much of Oman farmland continues to be watered by flood/alfaj system. Flood irrigation is the most used system for fruit/date farms, while vegetables are primarily grown using drip/modern irrigation (Figure 2). Drip irrigation has the advantage of only irrigating in the crop row, but a disadvantage of possible salt accumulation on the surface. Flood irrigation is less efficient for a single crop, but is used in Oman to irrigate multiple crops in the same field, and has the advantage of leaching salts. Carbon, nitrogen, and phosphorus cycling dynamics are likely to be quite different in these two systems, and both types of farming systems have been studied in Oman, but to our knowledge, there are no studies with direct comparison of carbon or nutrient cycling. In both irrigation systems, due to the coarse/sandy texture of most soils of Oman, leaching of nutrients is an issue, and virtually all cropped land in Oman receives irrigation in one form or another, due to the low annual rainfall. Perennial forages are grown using both systems, while field crops are more often planted in the traditional aflaj irrigated areas of Oman, and may be planted as monoculture, or as understory crops within a planting of perennial fruit trees.

The tradition of integrated crop and livestock farming has carried into the present, in terms of recommended fertilization practices, and actual use of fertilizers and manures on cropped soils. Though chemical fertilizers are used on an average of 59% of agricultural land (Table 1, statistics from MAF 2015), there is an estimated 88% of land receiving non-processed organic fertilizer/manure. In addition, about 45% of land also receives processed organic fertilizer (compost). The percentage of land receiving fertilizer is slightly higher in North and South Al Batina, which are heavily cropped with vegetables and forages (72 and 64% respectively), but these lands still receive non-processed organic fertilizer on about 84% of the land. The percentage of land receiving organic fertilizer goes up in Governates such as Ad Dakhiliya and Dhofar to 92%. Pesticides are used on approximately 59% of agricultural land, on average.

In addition to tradition and the presence of livestock on farms in most regions of Oman, the Ministry of Agriculture specialists recommend annual fertilization with non-processed manures at rates ranging from 10 to 60 kg per tree for crops such as mango and coconut (Hameed and Habees, 2014; Al Jabri, 2003), depending on the tree age and size. Organic manure is also recommended at fairly high rates for crops like sorghum, alfalfa and Rhodes grass (Table 2) (Ghabeshi, 2005), but at lower rates for most vegetable crops (Table 3)(Anon, 2011). The application of mineral fertilizers is also recommended, in addition to the nutrients that will be released from organic matter.

Table 2. Recommended rates of organic manures and fertilizer products for example field crops in Oman (Ghabishi 2005)[1] and rates applied according to a survey of small, medium and larger vegetable farms in Oman (Al Salmi, 2020)[2].

	Recommended Rates (kg/ha per season)[1]			Rates applied by small, medium and large farms in Oman (kg/ha per season)[2]		
	Recommended for sorghum	Recommended for alfalfa	Recommended for Rhodes grass	small farm (less than 5 feddan)	medium farm (5 to 20 feddan)	large farm (more than 20 feddan)
organic manure	14,286	14,286	14,286	1,919	4,302	5,588
NPK (balanced)				369	567	490
Urea fertilizer (46% N)	357	60	714	221	888	329
Other fertilizer				76	55	174
Triple super phosphate (46% P_2O_5)	238	238	238			
Potassium sulfate (48% K_2O)	238	119	476			

Table 3. Recommended rates of organic manures and fertilizers for selected vegetable crops in Oman (Anon. 2011)[1], rates applied according to a survey of vegetable farms in Oman (Al Salmi 2020)[2] and recommended for sandy soils in Florida (ref: Maynard and Hochmuth. 2007)[3]

Rate applied (kg/HA per season)	Recommended for Eggplant (Oman)[1]	Applied to egg-plant[2]	Recommended for Eggplant (U of FL)[3]	Recommended for tomato (Oman)	Applied to tomato (Oman)	Recommended for tomato (U of FL)	Recommended for okra	Applied to okra	Recommended for okra (U of FL)
organic manure	107[1]	2,857[2]		107	3,095		107	2,619	
N	192	319	224	274	332	224	219	327	135
P_2O_5	82	124	1683	82	148	168	82	110	168
K_2O	143	168	179	171	196	168	114	151	168

Notes: [1]the amount of NPK in the Oman organic manure was small (less than 3 kg/ha) and so was not added to the NPK totals.

[2]The estimated NPK value for the organic manure was added into the total nutrient values by using the average manure values of NPK from sheep, horse and feedlot (from Table 4.3 pg 151 in Maynard and Hochmuth, 2007, which was 2.53% N, 1.20 % P_2O_5, and 2.73% K_2O).

[3]The recommended rates for the University of Florida are for sandy soils with very low soil P tests. If there is more soil P, the recommended rates would decrease from these values (Source: Table 4.32 pg 225 in Maynard and Hochmuth, 2007)

A recent survey of 198 farms in the Al Batinah Governates, North Sharqiyah and Ad Dakhiliyah, conducted between February 2018 and April 2019 allows us to compare recommendations and actual farm practices (Al Salmi, 2020). The applied rates of urea fertilizer are in the range of the recommended rates (Table 2, recommended rates from Ghabishi, 2005) and will depend on the crop grown. For example, lower rates would be recommended for nitrogen fixing crops like alfalfa. The rates of P_2O_5 and K_2O are difficult to compare, because the survey only recorded the use of balanced fertilizer, which would likely be a 10-10-10 or 20-20-20 mix of N, P and K. The organic manure applied by farmers is lower than the recommended rates for forage crops, but is still substantial, at between 2 and 5.6 metric tons per ha for small, medium and large farms.

The rate of organic manure recommended to farmers is much lower for vegetable crops such as eggplant, tomato and okra (Table 3, recommendations from Anon, 2011), at only 110 kg per ha, as compared to 2.6 to 3 tons per ha reported as applied by the surveyed farms (Al Salmi, 2020). When the estimated nutrient values in this manure are converted to N, P and K equivalent values, the rates applied by farmers are similar to recommendations for both Oman, and for sandy soils in Florida, USA. In general, we see the farmers might be over-applying nitrogen to all 3 crops. This may be due to the slow release nature of nitrogen from the organic matter source, or to compensate for leached nitrogen due to constant irrigation, whether it is drip or flood.

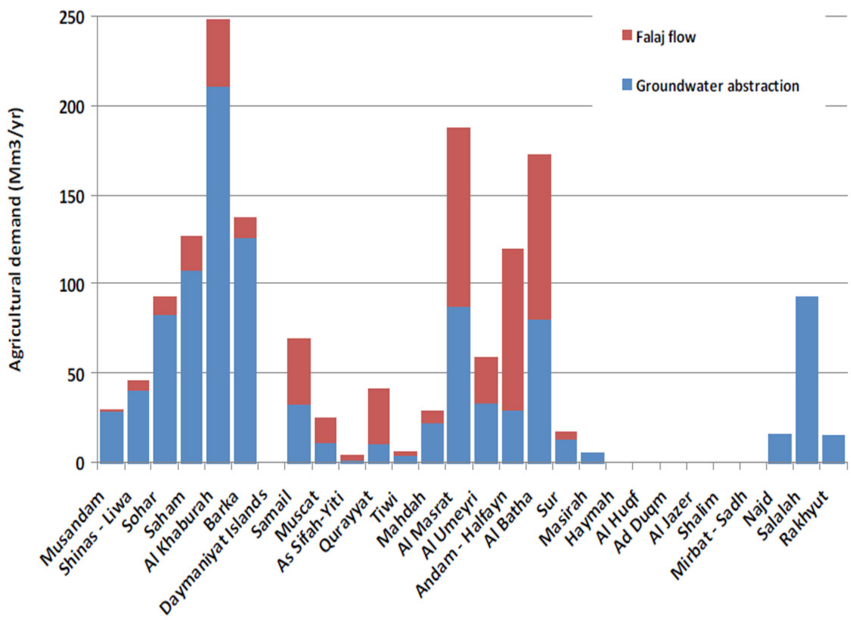

Figure 1. Agricultural abstraction of water from groundwater and falaj flow by city/region from Northern Oman to Southern Oman (reference: Ministry of Regional Municipalities and Water Resource, 2013).

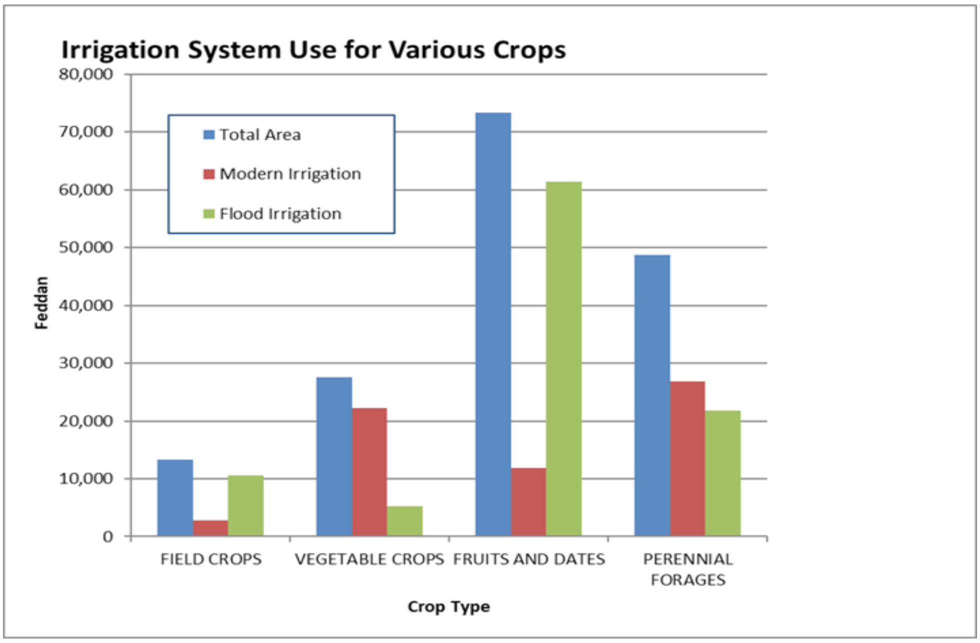

Figure 2. Comparison of area supplied by drip vs. flood irrigation systems by type of crop in Oman (MAF, 2015).

Trials with Fertilizers and Organic Amendments

Though manures and composts are widely used in Oman, fertilizer is also used, both alone, and in combination with organic inputs. The Ministry of Agriculture & Fisheries (MAF) has conducted some field trials to determine optimal nutrient needs of many crops. There is some risk of under-fertilization, and under-yielding of crops, but also the risk of over-fertilization, especially in fields with a history of manure use, and also in the now widely used and intensively cropped greenhouse production systems. In addition, different types and qualities of organic amendments are sold by suppliers or by plant nursery stores with a lack of knowledge in terms of their behavior in soil and plant systems (Al-Ismaily, 2011). In Oman, there are now also 3590 greenhouses with a total area on 344 feddan, and 238 shade-houses on 188 feddan (MAF, 2015). These tend to be intensively cropped and fertilized, and are at risk of over-fertilization. For example, one grower in Oman was instructed by their input supplier to put 72 bags of compost for a new planting of tomatoes in one greenhouse (pers. comm. one of the authors). If one does the math, based on the average size of bag and % nitrogen in compost, that is equivalent to 41,143 kg of compost per ha, or 823 kg/ha of nitrogen. This is far above the recommended levels (Table 3), and could result in high soil EC levels, reduced plant growth, and reduced fruiting of tomato due to too much N. It also makes the plants more susceptible to disease. There are also hydroponic greenhouses in Oman, which have some sustainability characteristics such as water savings. However, since they have no soil, and are not allowed under European organic certification guidelines, they are not covered in this review.

Some of the experiments described in this section only look at the rate of mineral fertilizer applied, but most use some combination of mineral fertilizers and compost or manure, and some also include a salinity treatment. Examples of fertilizer response trials in Oman include those on bananas (Al Harthi and Al-Yahyai, 2009; Al Busaidi, 2013). In a trial conducted at the Agricultural Research Center in Rumais, Oman, banana yield after 18 months was lower in the high salinity plots as compared to the low salinity treatment. However, there were no significant differences among the other treatments which included two fertilizer treatments, three compost+mulch treatments and a dairy manure treatment (Al Busaidi, 2013). The fertilizer was applied at a rate of 400 g/plant nitrogen as urea, split over 7 application times, and the manure and compost applied at rates of 39 and 22.2 kg/plant at the time of planting, respectively. Phosphorus, potassium and micronutrients were also applied to the fertilizer treatments. An experiment with in Salalah compared zero, 300, 600 and 900 g/plant split into 5 applications over 12 months (Al Harthi and Al Yahyai, 2009). In addition, 20 kg of organic compost was added to each plant twice, and all plants received micronutrient foliar spray 3 times. Results showed that the optimal treatment of 600 g N/plant was significantly higher than the other treatments. Yields were reduced at the 900 g N/plant level. There was no significant difference between the control and the 300 g N/plant treatment.

An experiment in Salalah with forage sorghum over two years compared 4 levels of urea nitrogen (0, 17, 34 and 69 kg/feddan), three levels of super phosphate and three levels of potassium sulfate (Anon, 2013c). There were no significant differences between the potassium and phosphorus level treatments, but the nitrogen applications were significantly different, with the highest yield at the highest level of urea application. The plots were watered with treated municipal wastewater, which would have resulted in the equivalent of 200 kg of nitrogen and 100 kg of phosphorus application per year in addition to the fertilizers.

In an on-going experiment with date palm seedlings, variety 'Khalas Aldahirah,' transplants from tissue culture propagation, planted in 2011 are receiving annual rates of 0, 250, 350, 500 and 650 g N/plant in the form of organic amendments. So far results show that the rate of 500 g N is optimal, with the lowest yield for the 0 N, and the second lowest from 650 g N (Anon, 2018). Replicated experiments in farmer's fields with garlic at 3 rates of fertilization found that the lowest rate gave the best yield (Anon, 2013a). There was no "control" check plot, and fertilizers were chemical formulations at rates of 97-76-83, 129-101-110 and 161-127-138 kg/Feddan NPK blends. It was not reported if organic amendments were also applied during or prior to the experiment.

Nutrient studies on tomatoes with fertilizers as compared to organic manure/compost vs. a combination found that the combination was the optimal treatment (Al-Ismaily et al., 2014), especially when subjected to salinity treatments of 6 or 9 dSm^{-1}. Fertilizer was applied at rates of 238 kg/ha for N, P and K, but the NPK value in the manure treatment was 333, 52, and 338 kg/ha for NPK respectively. This experiment was conducted on land that had previously been fallow for 15 years and started with low levels of all nutrients. Generally, the N in manure is slowly available, and should have been applied at a 2x rate, assuming only half would be available in the first year, but in this experiment was only 1.4x the fertilizer N rate. The half-fertilizer and half-manure rates combined the best properties of both materials, with some N quickly available at the beginning of the experiment, but some also released later from the manure source.

Organic farming promotes the use of manures, composts, cover crops, and mulches, but in moderation (Brinton 2001; Barker 2010). The benefits of compost are well known, and may be especially helpful on saline soils (Oo et al., 2015; Ouni et al., 2013). Compost quality is an area deserving of more research however, as different composts from different feedstocks have different properties (Al-Ismaily, 2011). International standards for compost have been proposed (Brinton, 2001), but have had limited implementation in most parts of the world, including Oman. In a greenhouse experiment at Sultan Qaboos University with broccoli and okra, two commercial composts were compared. One was a plant-based compost, and other included livestock waste. There was no significant difference in the performance of the composts on plant growth or soil properties, but there was a significant benefit of compost as compared to the no-compost control (Al Busaidi, 2017). The compost significantly increased the soil organic matter levels, but also raised the EC, so again, should be used in moderation and in conjunction with soil testing.

Previous nitrogen and carbon studies conducted in Oman found that though significant amounts of nitrogen are lost through volatilization, both carbon and nitrogen can accumulate in vegetable crop rotations with organic amendments instead of fertilizer (Siegfried et al., 2011; Jordan et al., 2015). Studies in the US have documented that carbon and nitrogen cycling are different in organic cropping systems, especially during the transition years (Liebhardt et al., 1989) and the use of organic amendments can reduce carbon and nitrogen losses from cropping systems as compared to fertilizer (Drinkwater et al., 1998). Cover crops like *Sesbania* can also add significant carbon and nitrogen to soils, especially at the beginning of a long term crop rotation (Al-Maskri et al., 2018)., even though in the context of Omani agriculture, the cost of the water to grow the cover crop would need to be considered.

Salalah has the potential to grow more of Oman's fruits and vegetables, based on the availability of land and water, and more moderate climate as compared to the Al Batinah region (Prathapar et al., 2014). Much of the agricultural land in Dhofar is devoted to animal based agriculture at this time, and only 27% of the 27,687 ha of agricultural land in Dhofar is currently cropped. A study of the nutrient status of soils and plant nutrient status for some horticultural crops in Salalah found that in general, phosphorus concentrations were nearly sufficient in all locations, potassium was deficient in about 50% of the crops, and nitrogen was deficient in most of the crops, as measured by leaf tissue samples (El Fouly and Shaban, 1999). A range of crops were sampled including the fruit crops banana, papaya, grapes, lime, other citrus and coconut, and the vegetables tomato and pepper. Soil samples showed that pH is generally high (average 8.4), EC is medium (average 2.37 mmhos/cm) and organic matter with one exception was low (average 1.81%). The soil texture was classified as a sandy loam, with 52% sand, 30% silt and 19% clay content. The calcium carbonate levels of the soil were very high, which agrees with the soil survey data for Salalah (MAF, 1992). Soil levels of phosphorus varied from medium to high, and soil potassium levels were low to very low. When farmers were asked about the fertilizers they used, it was difficult to get accurate information, but in general, nitrogen and phosphorus fertilizers were being used, but very little potassium or micronutrients. High amounts of organic manure were being used on the vegetables, along with intensive use of pesticides.

In summary, the fertility needs of each type of crop may be different, and the cropping and fertilization history for each site is different. There is a need to do these trials based on site specific conditions, and to report both the current and previous additions of organic matter that could make a difference in the nutrient release during the experiment, and also the recommended rates based on the experiments. Organic amendment sources and compost quality may also be different, and there may also be interactions between irrigation practices and soil fertility which should be studied.

Experiments with Municipal Waste and Wastewater

Though not allowed for certified organic production systems, treated municipal (human) waste, waste-based compost, and treated wastewater offer other strategies for soil improvement and nutrient application in Oman. Recent reviews suggest that all of these can be used safely, though attention needs to be paid to government standards, regulations, and policies for use (Hussain et al., 2019; Khaliq et al., 2017a). In Oman, there are currently 400 wastewater treatment facilities in the country (Husain et al., 2019), and much of the wastewater, especially in the municipality of Muscat, the largest city, it is being used to water landscape plants for city beautification, parks, and ornamental gardens. Research is being done to evaluate the safety for use on crops on some test farms.

One of the risks of using treated wastewater is the presence and accumulation of heavy metals, which can be avoided by keeping them out of the seawater source stream, or by growing plants that do not take up heavy metals, and monitoring accumulation in the soil. Another risk factor is the presence of human pathogens. These can be reduced or eliminated by using tertiary water treatment systems, or by growing crops not destined for human consumption. However, two new risks have emerged with the use of treated wastewater; pharmaceuticals and personal care products (Al Farsi et al., 2018a; Al Farsi et al., 2018b). In an experiment with both low levels and spiked samples with pharmaceuticals, two were not detected in soil or plant samples, one antibiotic accumulated in radish roots, and a second antibiotic was translocated into the radish plant (Al Farsi et al., 2018a). A review of the literature for the uptake of personal care products from wastewater found that more than 100 have been studied in several countries, and that the uptake depends on the chemical nature of the product and also the plant (Al Farsi et al., 2018b). Many of these have the potential to reach and accumulate in plant tissue. The research on risk and its possible impact on human health is still unknown.

A study on the use of grey water for home gardening, collected from a newly built home in Oman, combined with kitchen effluent supplied nutrients to plants and did not show any harmful chemical or biological contamination (Al Ismaili et al., 2017). In the same study, cost of the greywater treatment system was calculated and found to be technically, environmentally and economically feasible. The system installed included a collection tank, a sand filter, and final treatment with chlorine prior to use in the garden. The water was tested on tomatoes and eggplant in a garden setting. Heavy metals in the treated greywater were negligible, and the Coliform and *E. Coli* levels were zero due to the chlorine treatment.

In contrast, a survey of urban residents in Al Seeb, Oman, found that many were not aware of the risks of using untreated waste or wastewater from septic tanks on their gardens (Shaharoona et al., 2019). In addition to the survey of 75 households, 7 soil pedons were excavated; 5 near garbage sites and 2 away from garbage sites, and were analyzed for heavy metals and microbial analysis. The questionnaire found that many gardeners were irrigating with untreated wastewater (25% untreated black water, 13% untreated greywater). Water samples were then collected from three wells and one septic tank. The soil samples showed that of the heavy metals, only cadmium was at an elevated level for 2 samples, but it was below the US and EU environmental standards. However, they found that garden soils irrigated with untreated black water were contaminated with a large number of pathogenic bacteria, including *E. Coli*, Staphylococcus, Salmonella, Shiglla, and fecal coliforms. In contrast, no pathogenic bacteria were detected in control soils only a few meters away. Only fecal coliform were found in soils irrigated with untreated greywater. None of the urban growers surveyed had ever tested their soil for nutrient levels or contamination. Some of the gardeners were using farm yard manure, some were using chemical fertilizers, and 19% were not using any fertilizer at all. One of the reasons gardeners gave for using septic tank waste to water the garden, in addition to a source of nutrients, was to save money on purchasing water from the municipality, but also to save money on having the septic tank pumped, which can be expensive if done on a monthly basis.

When treated wastewater is used, some of these risks can be avoided. Date palms leaves, fruits and soil were sampled from areas irrigated with treated wastewater for at least 7 years and compared to dates watered with groundwater. Results showed that heavy metals in the groundwater and treated wastewater were within international standards, and that heavy metals were at acceptable levels in the soil, plants and fruits (Al Busaidi et al., 2015).

Wastewater only has the potential to add nutrients, and to replace some or all of the irrigation water that would have been required. Municipal sludge and/or compost has the additional benefit of improving the soil through the addition of organic matter (Khaliq et al., 2017a). In one experiment white radish and green beans were grown with either chemical (NPK) fertilizer or Kala compost (from municipal waste) and watered with either groundwater or wastewater (Khaliq, 2017b).

Results showed that the yield and chlorophyll contents of both were higher with Kala compost as compared to the NPK fertilizer. Analysis of the soil and plants did not show any risk of heavy metal accumulation. The treated wastewater in this experiment did not show any statistically significant differences from watering with groundwater. The Kala compost resulted in higher soil total organic carbon levels as compared to the fertilizer.

Experiments in Barka and Hamra looked at the effect of Kala compost on cucumbers in commercial greenhouse production systems (Al Busaidi et al., 2017). High levels of nutrients were found in the soils after application, and also high EC levels at the start of the experiment, which were lowered during the course of the experiment through leaching by irrigation water. Most heavy metals were low in both soil and plants, though nickel was high in some of the plant samples, but not in the soil. It was concluded that the Kala compost is safe to use, and one of the greenhouses had applied Kala compost for 5 consecutive years.

In a third experiment in Oman, Kala compost was compared to inorganic NPK fertilizer or a mix of the two in open field plots with the crops cucumber, tomato, cabbage, lettuce, carrot and potato (Al Busaidi and Ahmed, 2016). The soil had sufficient amount of nutrients for good crop growth in all treatments, though yields were generally higher with the Kala compost as compared to the NKP treatment. No adverse chemical or physical plant or soil problems were noted. Chemical analysis of plant samples did not show any accumulation of heavy metals, and all measured elements were within the safe limit for human consumption. Kala compost is manufactured in a highly controlled process that combines the treated sludge from the Muscat municipal waste treatment plant with chipped wood and yard waste. The nutrient value of the Kala compost used in the trial was 3.17% N and 1.4% P, potassium was not measured, and fecal coliform levels were zero. In the experiment, the soil organic matter levels were highest with the Kala compost treatment.

An experiment conducted on tomatoes comparing Kala compost and Al Mukassab (commercial, animal waste-based compost) at two rates found no significant difference between the rates used and the two products for tomato production (Anon, 2013b). The tomatoes were field grown during the 2012-2013 growing season, the composts had identical nitrogen concentrations (2.5%), and the rates of 10 and 20 ton/ha were compared.

Carbon Added to Soil as Mulch or Biochar

Even though it is documented that manures and composts are used in farming systems in Oman, there is still much farm-generated biomass goes to waste through off-farm disposal or burning. Much of this waste could be a valuable resource and be used as mulch or made into biochar. Only weeds and diseased plants should be excluded. Date palm prunings and mango wood could be utilized at the farm level with minimal processing (Al Busaidi et al., 2017). The benefits of mulches from date palm leaves on saline soils in Oman has been documented for tomatoes (Wahaibi et al., 2007) and also for sorghum (Al-Rawahy et al., 2011). The tomato experiment included date palm mulch, plastic mulch, and bare ground control, at 2 irrigation salinity levels; EC 3 and 6 dS/m. Date palm mulch resulted in higher tomato fruit yield, lower soil temperature and lower soil EC levels (Wahaibi et al., 2007). A similar result was found in the sorghum experiment, which also included date palm mulch, black plastic mulch, and control at the same two irrigation salinity levels (Al Rawahy et al., 2011). Again, the date palm mulch resulted in better yields, lower soil salinity levels. It was also noted that soil temperature was lower, and soil moisture was higher with the date palm mulch.

Other experiments have noted benefits of organic mulches on saline soils. Municipal solid waste and date palm mulch both improve the soil carbon and nitrogen levels, as well as microbial biomass and several soil enzymes that were measured under saline conditions (Ouni et al., 2013). Two recent reviews on soil salinity and organic wastes note that waste recycling of farmyard manures, industrial byproducts, and other organic materials provide an effective way to restore soil quality in salt affected soils (Diacono and Montemurro, 2015; Ahmed et al., 2013).

Farm generated waste or biomass could further enhance soil quality if used as biochar, which is the burning or pyrolysis of a carbon source without oxygen, to retain most of the carbon and not release it as CO_2. Recent reviews have shown that biochar can improve crop productivity by increasing nutrient content, nutrient use efficiency and water holding capacity (Hussain et al., 2016; Aon et al., 2015). Generally, soil carbon levels increase with increasing amounts of added biochar. The effect on crop yield will vary, depending on the quality and source material of the biochar, which affects the nutrient content and carbon/nitrogen ratio of the product. Application of biochar to fertile soil often results in less effect on plants than application to nutrient poor soils. The effect of biochar on microbial communities has shown both positive and negative effects (Palansooriya et al., 2019). Biochar can increase the amount of carbon and increase the surface area/micropores for microbial growth in the soil, but the carbon is not always readily available to the microbes. Under some condition, the pyrolysis process can produce aromatic hydrocarbons, which can be toxic to microbes.

In an experiment in Oman, activated charcoal and tannins were added to compost and to soil in an effort to reduce the leaching and volatilization of nutrients. Tannins applied directly to the soil reduced N_2O emissions and NH_3 volatilization (Jordan et al., 2015). However, emissions of all gases increased in the compost and charcoal amended soils, but the organic soil carbon levels also increased with these compost and charcoal as well. In a second experiment, tannins and charcoal were either added to the soil with goat manure, or fed to the goats, and then the enriched manure was applied to a sweet corn-radish crop rotation (Ingold et al., 2015). All of the treatments increased the soil organic carbon levels as compared to the NPK control plot, and also increased the soil microbial respiration. In this study, there were no additional measurable effects of the charcoal or the tannin addition to the manure, as compared to the manure alone.

In two trials in Oman with cucumber seedlings under growth chamber conditions, the addition of biochar resulted in higher soil organic matter levels, higher levels of water soluble potassium and sodium bicarbonate (Olsen method) extraction of phosphorus, and in one of the two experiments, greater plant biomass (Al Toobi, 2018). The plants grown with biochar had decreased levels of sap NO_3 and increased sap K, but showed no change in sap sodium (Na). A greenhouse experiment with corn and cucumber with biochar added at 5 or 10% by mass, found no effect on plant height, biomass, or chlorophyll content (Khan et al., 2018a). The soil pH did not change, but soil EC increased with increasing rates of biochar. In a second greenhouse experiment with okra and broccoli, EC levels were initially higher with biochar, but the same as the control at the end of the experiment (Al Busaidi, 2017). The pH was not affected by biochar, but the soil organic matter levels and water holding capacity were higher. In this experiment, plant height, chlorophyll levels and plant biomass were not affected. In all three experiments, biochar was made on site from mango wood prunings, using a home-made burning apparatus (Al Busaidi et al., 2017).

In another greenhouse experiment, local wood biochar, (*Maerua crassifolia*) was compared to wood ash, and also to biochar and ash made from local wild grass, *Saccharum kajkaiense* (Al Kindi et al., 2018; Khan et al., 2018b). Currently, many types of biomass from farms is burned and the ash applied to fields, and the biochar might be an alternative to ash. Both the wood and the grass biochar increased the soil organic matter levels, and the wood ash increased the levels of soil potassium. Soil EC levels were increased by wood ash, but not the biochar; soil sodium levels were unaffected by biochar or ash. Neither the biochar nor the wood ash resulted in an increase in plant biomass, but the grass ash resulted in higher okra plant dry weight.

Experiments conducted in Saudi Arabia with biochar from date palm residue found that biochar produced at lower pyrolysis temperatures (300 and 400 C) were most effective at promoting wheat growth, but only when applied with fertilizer (Alotaibi and Schoenau, 2019). Water retention in the soil was also improved with the low temperature biochar, especially when combined with incubation in the soil for up to 60 days. Soil bulk density was decreased, and soil porosity increased more with the higher temperature biochar (up to 600 C). Organic matter and CEC was increased as compared to the control only for the biochar at 300C; pH and EC was not significantly different among all treatments.

Biochar also has the potential to be of benefit in soils affected by abiotic stress such as salinity and drought. An investigation of biochar derived from rice straw and the effects on plant growth and certain metabolic activities of salt-stressed cowpea (*Vigna unguiculata* L.) showed significant plant growth reduction under the salinity treatment compared to control (Osman et al., 2019). Seed germination was enhanced with the application of rice straw-derived biochar. Further, biochar increased the photosynthetic pigments and ascorbic biosynthesis. Their results found the highest growth rate and plant physiological traits at 75% NPK combined with the biochar amendment. They concluded that the rice straw-derived biochar reduced the extra use of chemical fertilizer up to 25%.

Biochar combined with microbial inoculation can also have benefits. The combined application of *Bacillus amyloliquefaciens* and biochar was more effective in mitigating the drought stress in wheat and enhanced the its productivity compared to the control. However, plant growth promoting rhizobacteria (PGPR) application alone did not show any significant increases in leaf chlorophyll contents (Zafar-ul-Hye et al., 2019).

It has been shown that under drought conditions biochar can increase the soil water holding capacity and its biological and physical properties. Biochar has shown decreased Na uptake under salt stress conditions and increased K uptake by the plants. Biochar may assist in lessening the drought and salt stress effects on plants (Ali et al., 2017). It has also been shown that biochar increases soil water holding capacity and plant productivity even under low water conditions (Zong et al., 2016). Moreover, it can reduce the trace element uptake in plants and enhance soil properties to reduce metal movement in the soil (Abbas et al., 2017).

Effect of Organic Farming Methods and Carbon Amendments on Soil Microbiology

Organic farming, in general, is a low external input farming system with a high reliance on healthy soil to sustain plant growth. High amounts of organic fertilizers are used in substitution for synthetic industrial fertilizers to sustain crop production (Hartmann et al., 2015; Liao et al., 2018). In addition, synthetic pesticides (herbicides, insecticides, fungicides, etc) are not allowed in organic farming, but 'alternative' pesticides, usually plant or mineral based, with low biotoxicity are used in substitution, in addition to preventative measures such as crop rotation, crop diversity, cover crops (Lupatini et al., 2017; Zarb et al., 2005). These changes in inputs are associated with complex responses of the soil microbial community diversity and function (Hartmann et al., 2015), leading to what is often described as better soil health and quality (Doran and Parkin, 2015; Lori et al., 2017; Yadav et al., 2018).

Although these terms are loosely described, organic farming systems aim at, and relies on, improving ecosystem health and sustainability (Lupatini et al., 2017). It has been suggested that organic farming systems not only lead to higher microbial biomass, activity and functional diversity, but they are also dependent on these microbial communities for nutrient cycling, plant nutrient uptake and crop yields (Liao et al., 2018). In organic farming systems, nutrient availability to plants is primarily achieved through the mineralization of plant and microbial organic compounds in soils (Araújo and Melo, 2010) and the conservation of an active soil microbiota through mulching, erosion control and organic matter inputs (Lori et al., 2017).

The mineralization of soil organic matter is carried out by soil heterotrophs, which accounts for the overwhelming majority of microbial species and also the majority of the soil microbial biomass. Although this is true for both organic and conventional farming systems, in organic farming, a significantly large soil microbial biomass represents an essential pool of rapidly cycling and readily available nutrients (Araújo and Melo, 2010; Hartmann et al., 2015; Liao et al., 2018). Soils on organic farms may contain nearly twice as much microbial biomass carbon, microbial biomass nitrogen, total phospholipid fatty-acids than conventional systems (Lori et al., 2017). This microbial biomass acts not only as a plant nutrient reservoir, but also as the source the biological processes or functions related to plant nutrient uptake, such as the production of extracellular enzymes involved in the soil organic matter decomposition e.g. carbohydrases, dehydrogenases, ureases and proteases (Lori et al., 2017).

Soil microbes regulate not only the carbon cycle processes, but nitrogen fixation, nitrification and denitrification, and nearly all the soil sulfur oxidation-reduction reactions (Yadav et al., 2018). Symbiotic diazotrophs (*Rhizobium*), rhizosphere bacteria and mycorrhizal fungi are considered to play a crucial role in mediating plant access to essential nutrients in organic farming (Zarb et al., 2005). Organic farming systems show a more complex fungal network with higher abundance of keystone mycorrhizae from the orders Glomerales, Paraglomerales, and Diversisporales than other farming systems (Banerjee et al., 2019).

Many recent studies have documented the effect of cropping systems on the response of microbial communities. On a global scale, soil microbial biomass, diversity and activity are higher in organic farming systems than under conventional farm management (Liao et al., 2018; Lori et al., 2017; Yadav et al., 2018). When organic farming systems are involved, these effects are often separated into the following components: a) organic fertility inputs and the cycling of soil organic matter, including crop residues and the use of legume-based cover-crops and green manures; b) the effect of controlling plant pathogens with 'alternative' and 'environmentally-friendly' pesticides; c) the effect of management practices such as tillage (depth, frequency) and crop rotation); and d) bioaugmentation of the soil with beneficial microorganisms (Lupatini et al., 2017; Zarb et al., 2005). In comparison to organic amendments, crop protection inputs (application of pesticides) has a significantly lower impact on soil microbes (Hartmann et al., 2015; Zarb et al., 2005). Other factors such as climate, soil management, type and life cycle of the crop also impact the microbial responses to organic amendments (Lori et al., 2017).

There are numerous studies that document the significant influence of both quantity and type of organic farming fertility inputs on soil microbial biomass size, activity, function and taxonomic diversity (Araújo and Melo, 2010; Hartmann et al., 2015; Liao et al., 2018). In general, the amount of the microbial biomass tends to increase with higher inputs of organic fertility amendments. Soil organic matter is also widely postulated as one of the key drivers of soil microbial diversity (Tsiknia et al., 2014), since chemo-organo-heterotrophs are predominant in all soils.

In summary, organic fertility amendments increase soil microbial species richness, diversity, heterogeneity, dominance, and results in a different microbial community structures in comparison to the use of mineral fertilization (Hartmann et al., 2015; Lupatini et al., 2017). Organic inputs, and organic farming management as a whole, increase the amount and diversity of keystone soil microbial species that are directly beneficial to plants (Banerjee et al., 2019; Liao et al., 2018; Yadav et al., 2018). Organic inputs create a less selective environment, allowing for a higher taxonomic diversity, whereas systems that do not receive organic inputs are dominated by oligotrophic organisms (Hartmann et al., 2015; Lupatini et al., 2017). This higher microbial biomass and taxonomic diversity are generally assumed to lead to a higher microbial functional redundancy, ecosystem stability, productivity and resilience (Torsvik and Øvreås, 2002).

Background soil properties such as soil texture, moisture regime, alkalinity and salinity condition the extent in which organic amendments will be effective in shaping a healthy soil microbial community. Among these, soil salinity is especially relevant for Omani farms. On the one hand, organic farming management may help to decrease salinization-related land degradation, and on the other, it will reduce the capacity of organic farming practices to sustain crop yields and a diverse and functional soil microbiome (Daffonchio et al., 2015; Lozupone and Knight, 2007; Rietz and Haynes, 2003). Soil bacterial communities are more prone to be affected by salinity than any other soil environmental conditions (Lozupone and Knight, 2007), tending to be enriched by halophilic Actinobacteria (O'Brien et al., 2019), Proteobacteria and Firmicutes (Das et al., 2019). Soil salinity decreases microbial biomass, respiration, enzymatic activities, diversity and increases the microbial metabolic quotient (Wasserstrom et al., 2017; Zhang et al., 2019). The metabolic quotient (an indicator of stresses) is usually unaffected by organic farming systems (Lori et al., 2017). The abundance of heterotrophic diazotrophic bacteria, essential for nutrient management in organic farming systems, are expected to be significantly decreased by soil salinity (Moradi et al., 2011), even though some research shows that high additions of organic matter can reduce the effect of salinity on plants.

Soil Microbiology Studies Specific to Oman

In terms of research specific to Oman, one of the earliest studies of soil microbiology documented the economically important fungal diseases (Waller and Bridge, 1978). This has been updated, as a more general list of fungi found in Oman (Maharachchikumbura et al., 2016). Surveys of the biological soil crusts have previously been one of the least explored areas for fungal diversity. However, in Oman 226 fungal isolates were recovered from both free-living and lichen-forming fungal communities in non-cultivated areas (Abed et al., 2012). These fungi were classified using DNA pyrosequencing, and the authors conclude that the desert crusts of Oman harbor a large diversity of fungal communities, and that the presence of lichens in these crusts improves soil characteristics.

Studies of date palm plantations and natural vegetation have found a large number of unique arbuscular mycorrhizal fungal communities (Al-Yahya'ei et al., 2011). Spore abundance and species richness was higher under date palms than native vegetation. Overall, 25 morphospecies were detected across both habitats, some of which seemed to be site specific. Two of the most globally abundant species (*Glomus intraradices* and *Glomus moseae*) were not detected. In addition, the study found four previously undescribed morphospecies and a considerable degree of molecular diversity seems to make these sites unique. In a follow-up study in north-central Oman using both morphological and molecular identification techniques, researchers recovered four species of arbuscular mycorrhizal fungi that had previously been described for the Arabian Peninsula, but are reported for the first time in Oman (Symanczik et al., 2014a). In a second study of the same region of north-central Oman, three new species of arbuscular mycorrhizal fungi were discovered and reported for the first time; two from non-cropped areas and one from a date palm plantation (Symanczik et al., 2014b). The authors conclude that further work is needed to understand the functional significance of these new taxa for conservation efforts and for agriculture.

The effect of a newly discovered endophytic fungus, *Talaromyces omanensis*, was studied on tomatoes subjected to drought-stress under greenhouse conditions (Halo et al., 2020). The presence of the fungus resulted in improved tomato characteristics under drought, such as shoot dry weight, root length, the number of flowers and fruit weight, as compared to the non-inoculated control. Even without the effect of drought, the inoculated plants performed better than the control. The inoculation lead to some interesting anatomical and chemical changes in the plants, such as increased phloem and cortex width, improved chlorophyll fluorescence, and higher concentration of gibberellic acid, which may enhance drought tolerance.

Both endophytic fungi and bacteria may help plants with other biotic stress, such as salinity, and the plants may also affect the rhizosphere. Date palm seedlings were inoculated with soil from existing date palms growing at the Sultan Qaboos University campus, and half were subjected to saline growing conditions (Yaish et al., 2016). DNA extraction and barcoding revealed that 30% of bacterial and 8% of fungal species had statistically different abundance when subjected to the salinity treatment. Some of the endophytes identified in this study were previously isolated from saline and marine environments. The authors suggested that there may have been a buffering effect by the host plant on the colonized root environment.

The microbes in the environment may also affect each other, and respond differently to moisture or other soil conditions. When four arbuscular mycorrhizal fungal (AMF) species from the Arabian desert were added to the crop, *Sorghum bicolor*, as the host plant in a microcosm experiment, they responded differently when an invasive species (*Rhizophagus irregularis*) commonly found in commercial inoculant was introduced (Symanczik et al., 2015). Three watering regimes were used. In the well-watered plants, hyphal length density was slightly higher, but not significantly different than when the commercial inoculant was added. However, the drought stressed treatment had the opposite result, with more hyphal length density in the native only (no commercial) inoculant treatment. Sorghum root and shoot dry weight were similar in both inoculant treatments in the watered treatment, but lower in the drying cycle and drought stressed treatment with the commercial inoculant. Other researchers have found that commercial introduced species sometimes do not survive when in competition native fungi (Hamel, 1996) or simply do not have any effect under field conditions, and when not in a sterile lab situation. A similar response can be seen with bacteria that were used as a manure inoculation. A native phytase-producing bacterium had significant reduction in abundance after only 6 days of incubation after inoculation (Menezes-Blackburn et al., 2016). In another experiment, E. coli survival time was reduced when introduced to soil with high microbial diversity, as compared to low diversity (Xing et al., 2019).

Many crops commonly grown in Oman benefit from mycorrhizal associations. Citrus, for example, are strongly mycorrhizal dependent (Ortas, 2012). Bananas with AMF benefit from enhanced plant nutrition and reduced nematode lesions (Jaizme-Vega and Pinochet, 1997), some protection from *Fusarium* wilt disease (Castillo et al., 2019), but there can be significant differences between colonization and benefits from the AMF that are different among different banana cultivars (Jefwa et al., 2012).

Compost can be a rich reservoir of beneficial fungi. An organic compost product originating from Oman made from green waste, wood, cow and buffalo manure, processed for 60 days, was sampled using direct plating methods on potato dextrose agar, and also through DNA extraction and identification (Al-Mazroui and Al-Sadi, 2016). Pyrosequencing detected 94 species, belonging to 6 phyla and 12 classes. Sixty-seven of the identified fungi are reported in Oman for the first time. Only 5 species were identified using direct plating. Though composts in the past had been considered potential sources of pathogenic fungi, this experiment found that the organic compost sample was dominated by saprophytic fungi and fungi with biocontrol characteristics. The three dominant fungi revealed by direct plating were *Aspergillus*, *Trichoderma* and *Penicillium*. Pathogenic species such as *Fusarium* and *Phoma* occurred at very low levels (less than 1% of the total species). In a similar experiment, 72 compost, organic fertilizer and potting media samples were compared from 14 countries. Fungal diversity analysis found high fungal diversity, especially in products from the Netherlands. Again, *Trichoderma*, *Aspergillus* and *Penicillium* predominated in most samples. Saprophytic fungi and fungi with biocontrol characteristics dominated in general, but *Fusarium* spp. were recovered at high frequencies in some samples (Al-Mazroui and Al-Sadi, 2015).

When both local and imported potting soils were compared to cultivated (farmed) and uncultivated soils of Oman, a surprising number and diversity of *Trichoderma* species were found in the uncultivated soils (Al-Sadi et al., 2015). Thirteen isolates, representing four species, were collected from 65 uncultivated soil samples with no known history of prior cropping. However, some samples were collected from dams, where soil that may have washed from farms upstream had accumulated. Fifteen isolates representing five species were obtained from 45 samples collected from farms growing crops such as date palm, cucumber, tomato, bean, alfalfa, pepper and potato. Twenty four isolates were obtained from 84 potting media samples produced in Oman, The Netherlands, Estonia, Germany, Finland, Latvia or the UK. Nine species were identified from the potting media isolates. On a percentage basis, the cultivated soils resulted in a higher frequency of both isolates and species per sample collected (33 and 11% respectively), but the authors were surprised by the number of species found in uncultivated soils, including *T. harzianum*, which is often used as a fungal inoculant. The percent genetic variation among the populations of *T. harizianum* obtained from the potting media, cultivated and uncultivated soil was very low, indicating high gene flow among these three sources. The authors also note that the high level of fungal diversity found on farms in Oman is a sign of soil health and makes it possible to find and select isolates with high antagonistic properties. Three species identified in this study had not been before reported in Oman.

Fungal diversity can vary between organic farms and conventional farms. A non-organic semi-oasis farm in Oman growing date palm, acid limes and cucumber was compared to an organic farm growing cucumber and tomato (Kazeeroni and Al-Sadi, 2016). The three crops on the non-organic farm had been fertilized using animal manures, but the cucumber also received conventional fertilizer and soil fungicide for the past 5 years. The organic farm crops only received organic fertilizer and had never received soil fungicide. Species richness estimates showed that the two organic farm samples were significantly higher than the three samples from the non-organic farm. The Shannon diversity values indicated that soils from date palm and lime have higher fungal diversity than cucumber on the non-organic farm, but that the organic cucumber and tomato soils had higher diversity than the non-organic cucumber. The diversity values were likely high for two crops on the non-organic farm, because manures are applied to the dates and limes, and there was no known use of fungicide. However, the cucumber on the non-organic farm had received fertilizers, and also soil fungicide, and both may have played a role in the lower fungal diversity. In this study, the soil organic carbon was highest under the date palm, probably due to repeated applications of manure, but not significantly different among the other crops, though it was slightly lower for the non-organic cucumbers.

Indigenous rhizobacteria can also have very specific plant protective properties. Thirty-eight native bacterial isolates from the rhizosphere soil of muskmelon and cucumber were screened for antagonism against *Monosporascus* root rot and vine decline disease in muskmelon. Five isolates showed antagonism grown on media in the lab, and one of the isolates, *Pseudomonas resinovorans*, reduced the incidence of vine declined by 93% relative to an infected control when used as a seed treatment or soil application (Al-Dagjaro et al., 2020). Native bacteria isolated from compost can suppress *Pythium* and *Fusarium*-induced damping off in cucumber (et al., 2020). Seven bacterial isolates from compost were screened, and two showed a significant level of antagonism. Both isolates were identified as *Pseudomonas aeruginosa* Soil application of this bacterial were effective in controlling damping-off of cucumber.

Plants can also benefit from endophytic bacteria isolated from wild plants. Endophytic bacteria live inside the plant, and can improve plant growth by improving plant nutrient uptake, modulating growth and stress related phytohormones, and improve plant health by targeting pests and pathogens with antibiotics, hydrolytic enzymes and by priming plant defenses (Afzal 2019). In

Oman, an experiment was conducted by first isolating endophytic bacteria from leaves of the mangrove tree, *Avicennia marina* (Ali et al., 2017a). From 28 bacterial isolates obtained, nine different genera were identified using DNA sequencing, and from these, two salt tolerant species (*Bacillus pumilus* and *Exiguobacterium* sp.) were chosen for further study on tomato. Tomatoes grown in a non-soil substrate were subjected to salinity stress and treated with these two strains of bacteria as a liquid inoculant. The inoculated tomatoes had significantly higher biomass, photosynthetic rate and pigment accumulation as compared to controls. The authors conclude that endophytic bacterial strains play a regulatory role in salinity stress, and possible mechanisms such as reducing oxidative stress by regulating antioxidants and related enzymes are discussed.

The type of crop and the growing conditions can also lead to different results when looking at the effect of microbial association benefits. For example, on tomatoes inoculated with *Trichoderma harzianum* and subjected to salt stress, the inoculated tomatoes without salt benefited from the inoculation in both fertilized and unfertilized experiments. However, once salt stress was introduced, only the non-fertilized tomatoes showed enhanced growth from the effect of the inoculation (Rubio et al., 2017). The type of crop can also make a difference, as well as the diversity of fungi in the inoculum. Wheat, barley, corn, and sorghum were compared in their response to either a single or a mix of four AM fungi. Wheat was unresponsive to any fungal treatment, and barley responded positively to the mix of four species, but only under low P conditions. The corn and sorghum responded positively to fungal inoculation, but only the sorghum responded to the increased fungal diversity and had higher colonization rates (Frew, 2019).

Most of the papers reviewed in this section focus on the species of microorganisms found in the soil, or the effect they have on the plant, whether it is to stimulate growth, protect from abiotic or biotic stress. Some of the species occur naturally in the soil or compost, and some have been introduced as inoculants, sometimes after being isolated from natural sources. In some organic farming literature, these broad categories of organisms and their effects are lumped together, along with others known for nitrogen fixation in a category called "biofertilizer" (Venkateswarlu, 2008). This is not a very precise term, and can mask the actual mode of action or mechanism responsible for the various effects. However, this term did not come into use by accident, but rather as a response to efforts to commercialize, patent, and sell microbial inoculants (Harman, 2010).

As noted in the diverse studies covered in this section, some microoransims have more than one effect on a plant, including both protection and growth promotion. If a company in the US or other country wants to bring a product to market as a "biopesticide," it can take as long as 6 years and up to $8 million for toxicology and efficacy testing, patenting, production and formulation in addition to identifying an effective organism. To register a product as a "biofertilizer, inoculant or plant strengthening agent" requires some of those same steps but can usually be accomplished in only 1 to 2 years and $1.8 million (Harman et al., 2010). Other models proposed that are even less expensive include government sponsored production, or community-based local production. The local model has been successfully used for strawberries in Costa Rica and in other countries, but quality control mechanisms must be in place to be sure that the final product is efficacious and not contaminated, but can be a cost-effective solution, with local production in close proximity in time and space to the end-users so that shelf-life of the product is not an issue.

On organic farms, including in Oman, some farmers purchase biological inoculants, especially *Trichoderma*, and add it to the potting soil mix for both plant stimulation and protection from root disease. However, for the *Trichoderma* or any other inoculant to work in the real world, the soil system must be conducive to growth. This effect is sometimes called "biostimulation," and is usually achieved by adding organic matter compounds such as manures or composts. This brings us back to the beginning of this review, where it was noted that many farmers in Oman are already adding both unprocessed and processed manures and composts. Future research in Oman should look at both the organisms, and the soil environment into which they are found or introduced, to better understand these processes as a whole system. Application of organic matter to the soil, especially composted crop, animal manures and mulches is also a recommendation in the "Strategic plant for combating water and soil salinity in the Sultanate of Oman" (Hussain, 2005).

Cropping Systems Research and Organic Farming

Over the years, long term cropping systems studies have made a significant contribution to our understanding of organic agriculture; especially in terms of nutrient and carbon cycling (Drinkwater et al., 1998), and also yield and pest management during the conversion to organic (Liebhardt et al., 1989). Most current textbooks on organic farming emphasize the need for a systems approach (e.g. Lockeretz, 2007; Francis, 2009; Barker, 2010). In a systems approach, organic treatments are not simply removing an input such as a synthetic fertilizer, but designing a diverse crop rotation with organic fertility amendments, non-chemical pest control, and different methods of planting, tillage, and mulching as compared to conventional monoculture systems. Understanding soil processes and differences between conventional and organic systems is key, especially when these are understood and studied as agro-ecosystems (Drinkwater, 2009).

Much relevant research has been conducted in Oman, in short term focused studies. For example, carbon and macro-nutrient balances were studied in organic vegetable systems within a crop rotation over a 2-year period in northern Oman (Siegfried et al., 2011). Tools such as genetic/molecular identification of beneficial soil microorganisms such as *Trichoderma* are also increasing our understanding of presence of these microorganisms in both cultivated and uncultivated soils in Oman (Al Sadi et al., 2015a), and fungal diversity in potting media and fertilizers used in organic systems (Al Sadi et al., 2015b). This level of detail is needed to explain the sometimes apparently contradictory results in the literature. For example, that *Trichoderma* can induce systemic resistance in host plants for a variety of plant diseases (Hoitink et al., 2006), but that the effect depends on whether the potting mix contains compost.

These complex details can be best studied in side-by-side replicated long term research plots, where complete control over soil conditions is established and monitored every year. Trials such as these have been conducted in the US since the early 1980's. A review of lessons learned from six of these experiments demonstrate accumulation of soil carbon, nitrogen, and other measures of improved soil health over the long term under organic management (Delate et al., 2015). Competitive economic returns are also realized from these cropping systems, but sometimes only after organic price premiums are considered. Diverse crop rotations along with organic amendments were key to good crop production, but also the level of experience of the farm manager made a difference in terms of the success of organic weed control. A review of 132 long-term studies of long-term experiments (greater than 10 years) world-wide also found that the application of manure resulted in gains in soil organic matter and Olsen P, but not always equivalent yields to treatments with inorganic fertilizer or manure plus fertilizer (Chen et al., 2018). The authors concluded that adding fertilizer to plots with organic amendments resulted in more resilience, especially if the crops were grown under tropical conditions or the inherent fertility of the soil was low.

In contrast, a long-term experiment from the Netherlands, summarized after 13 years found less variability (lower coefficient of variation) in yields or the organic as compared to conventional systems with fertilizer, after initially finding lower yields in the organic plots in the first few years (Schama et al., 2018). Soil properties showed significantly higher soil organic matter, soil aggregates, nutrient availability, and soil biota in the organic systems. The organic system also resulted in lower groundwater nitrate concentrations and fewer plant parasitic nematodes.

An analysis of 14 long term field trials in the US and the UK, ranging from 20 to 120 years, was used to compare the effect of fertilizers and manures (Edmeades, 2003). Manured soils had higher contents of organic matter and soil microfauna, and were also higher in P, K, Ca and Mg in the topsoil, and nitrate N in the subsoil. They also had lower bulk density, higher porosity, hydraulic conductivity and aggregate stability as compared to fertilized soils. This experiment cautioned that over-application of manures over a long period of time can lead to excess P and the potential leaching of nitrate if not applied in moderation, and it recommended to match the rates of application to the nutrient needs of the crops.

Long-term in-ground greenhouse production systems (also called high tunnels), can also result in changes in soil properties over time as compared to field plots (Knewtson et al., 2012). After eight years of organic production the total carbon and particulate organic matter (readily available carbon) were both increased in the organic high tunnel and open field plots, but not in conventionally managed/fertilized high tunnels or field plots, with a vegetable crop rotation. Soil salinity increased slightly in the high tunnels as compared to the field in both systems but was not high enough to be detrimental to crop growth.

Organic Farming in Oman - Benefits and Potential

In addition to soil improvement, other benefits of organic farming have been well documented in terms of environmental quality, and also human health. In Oman, over-fertilization has been found to contribute to high levels of nitrate in groundwater supplies (Ahmed et al., 2001). Mis-use of both legal and illegal pesticides in Oman has also been documented in a farmer survey (Al Zadjali et al., 2014), and pesticide testing for shipments of fruits and vegetables going into and out of Oman has become mandatory, due to un-safe levels of pesticide residue detection on some shipments.

Several reviews have revealed links between human pesticide exposure and certain forms of cancer (Bassil et al., 2007), and also links between pesticides and other negative non-cancer health impacts (Sanborn et al., 2007). Organic food has been demonstrated to have lower levels of pesticide residues than non-organic foods (Smith-Spangler et al., 2012), though similar levels of nutrient content (Dangour et al., 2009). However, other research found higher levels of anti-oxidants and other beneficial phytochemicals in organic foods (Zhao et al. 2006). Children who eat diets of organic food consistently for 2 weeks have less pesticide metabolites in their urine than the control group (Curl et al., 2003; Lu et al., 2006), so less pesticide in the diet can translate into less pesticide in the body.

But does eating organic food can also lead to a lower risk of cancer? Two extensive, long term co-hort studies have been conducted in France (Baudry et al., 2018) and in the UK (Bradbury et al., 2014). Participants were asked to report their consumption of organic foods, and data were controlled for other risk factors such as smoking, age, and gender then co-horts were followed over a period of years. The study in France over 7 years included 68,946 participants and found links to several types of cancer in the non-organic consumption group. The UK study included 623,080 individuals over 9 years and found a statistically significant reduction in the incidence of non-Hodgins forms of leukemia for the group that consumed organic foods.

Globally, organic food and drink sales have been growing at a rate of about 20% per year for at least 2 decades, and has reached $97 billion USD. The land classified as "certified organic" has increased from 11.0 to 69.8 million ha from 1999 to 2017 (Willer and Lernoud, 2019). In addition, there is probably much land that is being managed organically but is not certified. The certification process is expensive, and requires registration with a certification organization, annual fees and inspections, in addition to documentation and records showing that only the allowed inputs are being used on the farm. Certification is usually only pursued by farmers with markets that will pay a premium price for organic products, or allow the farm to achieve product differentiation or distinction in the market.

Attitudes towards organic farming in Oman seem to be generally positive. A recent survey conducted at a farming conference in Oman found that 50% of the farmers preferred to use organic compost, 30 % preferred organic non-composted manures, and only 6% preferred to use chemical/synthetic fertilizers (Al Toubi, 2015). She also found that when asked about the possibility to adopt organic farming systems in Oman, 68% believed it is possible, while 19% thought it isn't possible due to pest and/or soil fertility issues.

Neighboring countries such as the UAE and Saudi Arabia have recently developed Organic Agricultural policies and certification schemes, demonstration farms, and also dedicated organic research plots (Hartmann et al., 2012). Al Toubi (2015) concludes her thesis by suggesting that long-term research is needed to address the future research questions for organic farming in Oman, while a general case was made by Drinkwater (2009) for long term ecological studies to move the science of organic farming forward. Understanding the soil food web, especially the microbial component, can help us design cropping systems for the future that are more resilient to drought (De Vries et al., 2012).

Benefits of Improved Soil in Oman

A note about audience for this research; there are 154,010 land-holding farms in Oman (MAF, 2015) on 315,011 Feddan (a Feddan is 0.42 ha). Of these, 90% of them are 2 Feddan in size or smaller (Figure 3). The 10% of farms that are larger than 2 Feddan are potentially selling product in the marketplace. Similar percentages are seen in the marketing statistics (MAF, 2015), as the Census of Agriculture shows that 88% of farms are growing primarily for family consumption, 9.5% to sell at markets in Oman, and 0.5% is sold into the export market. The remainder is unknown or sold for processing. Research on soil quality, and the results from the research needs to be disseminated to both market and non-market oriented farms, of various size categories, in addition to farms on different soil types, crops, and using different irrigation systems described in the earlier sections.

Urban home gardeners are also an important recipient of this information, as many are growing fruits and vegetables for home consumption (Al Mayahi, 2019). Many small farms/gardens may already be using primarily organic practices, and may not care about certification, but could be encouraged to continue to use their soil and water resources wisely.

A recent survey of 125 households in a suburban area in Muscat Oman, found that 57% of them had home gardens. Of those that had a garden, 75% were growing fruit crops, and 48% vegetable crops, in addition to ornamental plants and grass (Al-Mayahi et al., 2019). In terms of soil fertility inputs, only 17% were using fertilizer alone, 54% were using only organic sources (compost, green manure and livestock manure) and 25% used a combination of fertilizer and manure. About 4 % didn't use any soil amendment or fertilizer, but the majority of the gardeners brought in new soil every year from an outside source (66%). Most were applying their fertilizer only once a year. In most cases, family members, or family members along with a gardener or a housemaid were caring for the garden, but in 27% of the gardens, the care was left up to either the housemaid or gardener. Sources of information for the gardeners in the survey area were the internet, family, friends, social media, neighbors and the plant nursery, in that order (Al-Mayahi et al., 2019).

In the farm survey (Al Salmi, 2020), the farm planting decisions were primarily made by the owner (85%), but with workers (8%), a farm manager (5%), or family (2%) also making the decisions on some farms. Sources of information for the farms include [note, survey respondents could select more than one answer] parents (82%), neighbors (65%), and extension agent (45%). Less mentioned sources were the internet/newspaper (32%), vegetable traders/processors (31%), consumers (25%) and input suppliers (14%).

Conclusion

This review has summarized the research on a wide variety of organic soil amendments used in agriculture, with a focus on the research that has been done in Oman. There are many benefits to using these amendments, ranging from increased organic carbon, improved water holding capacity, better habitat for soil microbial diversity and function, resulting in better nutrient mineralization, plant protection, and crop yield. Amendments vary from organic mulches, compost, manures, and municipal biosolids and wastewater. Municipal biosolids and wastewater are not allowed in certified organic farming, but have beneficial effects on the soil and its properties, and are good for the environment as long as the anti-quality factors that may be present are either

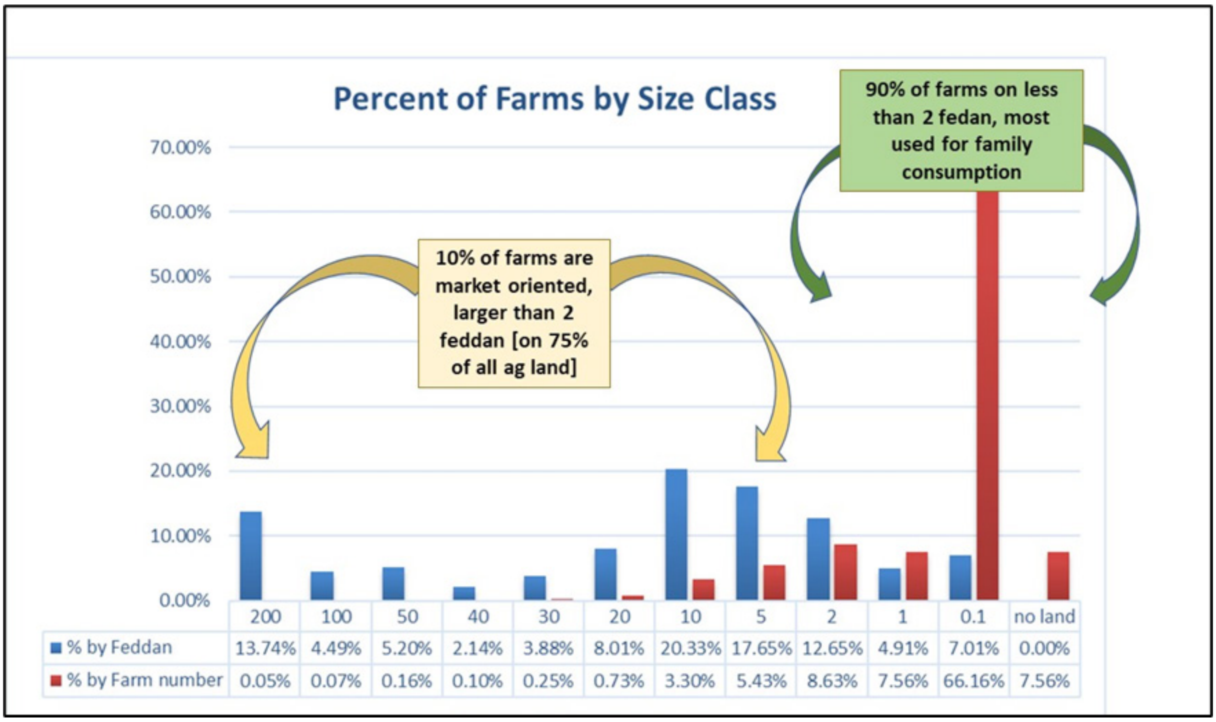

Figure 3. Number of farms and area by size class in Oman (MAF, 2015).

controlled at the source, or tested and only applied to crops not for human consumption. The audience for this research varies from home gardeners, to family farms with small plots for home use, to larger scale farms that grow for both domestic and international export markets. Crops range from forages, grains, fruits and vegetables, and irrigation systems include both drip from well water and flood irrigation from springs/aflaj. The soils suitable for agriculture in Oman are limited to only 6.5% of the total land area, and are further limited by soil and water salinity and the availability of water. However, the papers summarized in this review show that organic matter added to the soil can help soils conserve water and reduce the effects of salinity. The most recent Oman Agriculture Census data shows that 88% of agricultural land received non-processed manures from some source, and 45 % received processed manure, or compost, which is positive. In addition, many of the Ministry recommendations for soil fertility for a range of crops include organic sources.

Organic farming is a trend that continues to grow world-wide at a rate of about 20% per year, and farmers who choose to get the organic certification usually enjoy a price premium for their products. Long term experiments on organic cropping systems show that it is possible to get the same yield using organic methods as compared to conventional NPK fertilizer and pesticides, but it requires excellent management, long-term application of organic fertility sources, and in some cases, cultural and biological control of some insect and disease pests. As the research in these areas progress, organic farming will become more feasible in the future, and is prepared to feed the anticipated 9 billion people. Continuous farming with only NPK fertilizer degrades land, contributes to the salt index, does not build organic matter, and has no long-term benefits. In addition, fertilizers and pesticides can leach into groundwater and are associated with higher rates of cancer. On the other hand, organic farming methods lead to increased organic matter in the soil, which can be achieved by using both traditional and non-traditional carbon sources. This increased soil organic matter is also associated with higher microbial biomass, diversity, and can result in enhanced crop growth and successful biological control of plant pathogens. This review has covered a wide range of topics, which are all inter-linked, and we hope this will provide a road map for future research in these areas including long-term systems studies on both farms and experiment stations.

Acknowledgement

The authors would like to thank Sultan Qaboos University and the Sultanate of Oman for funding numerous research projects and graduate students over a several-year period, including, but not limited to the Dean's Research Fund, Internal Grants, Research Council Grants and His Majesty Trust Fund Research Grants.

References

Abed RM, Al-Sadi AM, Al-Shehi M, Al-Hinai S, Robinson MD. (2012). Diversity of free-living and lichenized fungal communities in biological soil crusts of the Sultanate of Oman and their role in improving soil properties. Soil Biology and Biochemistry 57: 695-705.

Abbas, T., Rizwan, M., Ali, S., Rehman, MZ, Qayyum, MF, Abbas F, Hannan, F, Rinkleble J, Ok YS. (2017). Effect of biochar on cadmium bioavailability and uptake in wheat (*Triticum aestivum* L.) grown in a soil with aged contamination. Ecotoxicology and Environmental Safety 140: 37-47.

Afzal I, Shinwari ZK, Sikandar S, Shahzad S. (2019). Plant beneficial endophytic bacteria: Mechanisms, diversity, host range and genetic determinants. Microbiological Research 221: 36-49.

Ahmed M, Al-Masehli M, Khan AJ, Al-Haddabi M. (2001). Impact of agriculture on groundwater quality in Northern Oman and possible ways to prevent nitrate leaching to groundwater. FGR. International Conference, 3, 201, Lisboa. Anais. p.p. 311-319.

Ahmed M, Hussain N, Al Rawahy SA. (2013). Management of saline lands in Oman: learning to live with salinity. in S.A. Shahid et al. (eds) Developments in Soil Salinity Assessment and Reclamation: Innovative Thinking and Use of Marginal Soil and Water Resources in Irrigated Agriculture. Spring Science+Business Media Dordrecht.

Al Busaidi A, Shaharoona B, Al Yahyai R, Ahmed M. (2015). Heavy metal concentrations in soils and date palms irrigated by groundwater and treated wastewater. Pakistan Journal of Agricultural Science 52: 129-134.

Al-Busaidi A, Ahmed M. (2016). Treated Municipal Wastes: Are They Contaminating or Enriching the Soil (Chapter 3), Soil Contamination - Current Consequences and Further Solutions, InTech - Open Access Publisher, Croatia. pp. 43 - 62.

Al-Busaidi A, Ahmed M, Shaharoona B. (2017). Evaluating continuous application of treated sludge on soil and plant productivity. Journal of Agricultural and Marine Sciences 22(1): 2-7.

Al-Busaidi KTS. (2013). Effects of organic and inorganic fertilizers addition on growth and yield of banana (*Musa* AAA cv. Malindi) on a saline and non-saline soil in Oman. Journal of Horticulture and Forestry 5: 146-155.

Al-Busaidi W, Khan MM, Janke R, Siddiqi S. (2017). Design and development of prototype biochar apparatus and initial tests of product characteristics. 2nd National Conference on Agriculture & Fisheries Research, Sultan Qaboos University, Oman. 3-4 April 2017.

Al-Busaidi W. (2017). Comparison and Efficacy Testing of Novel Soil Amendments Used in Organic Farming Systems in Oman. MSc thesis. Sultan Qaboos University, Muscat, Oman. 54 pp.

Al-Busaidi W, Khan M, Janke R, Al-Sheriqi M, Al-Yahyai R. (2020). Efficacy of soil amendments in organic farming systems. Agrociencia Journal 54(1): 1-31.

Al-Daghari DSS, Al-Sadi AM, Janke R, Al-Mahmooli IH, Velazhahan R. (2020). Potential of indigenous antagonistic rhizobacteria in the biological control of *Monosporascus* root rot and vine decline disease of muskmelon. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science 70(5): 1-10.

Al Farsi R, Ahmed M, Al Busaidi A, Choudri BS. (2018a). Assessing the presence of pharmaceuticals in soil and plants irrigated with treated wastewater in Oman. International Journal of Recycling of Organic Waste in Agriculture 7: 165-172.

Al Farsi RS, Ahmed M, Al Busaidi A, Choudri BS. (2018b). Translocation of pharmaceuticals and personal care products (PPCPs) into plant tissues: A review. Emerging Contaminants 3(4): 132-137.

Al Ghafri HM, Velazhahan R, Shahid MS, Al Sadi AM. (2020). Antagonistic activity of *Pseudomanas aeruginosa* from compost against *Pythium aphanidermatum* and *Fusariuim Solani*. Biocontrol Science and Technology 30(7): 642-658.

Al-Harthi K, Al-Yahyai R. (2009). Effect of NPK fertilizer on growth and yield of banana in Northern Oman. Journal of Horticulture and Forestry 1: 160-167.

Ali A, Shahzad R, Khan AL, Halo BA, Al-Yahyai R, Al-Harrasi A, Al-Rawahi A, Lee IJ. (2017a). Endophytic bacterial diversity of *Avicennia marina* helps to confer resistance against salinity stress in *Solanum lycopersicum*. Journal of Plant Interactions 12: 312-322.

Ali S, Rizwan M, Qayyum MF, Ok YS, Ibrahim M, Riaz M, Arif MS, Hafeez F, Al-Wabel MI, Shahzad AN. (2017b). Biochar soil amendment on alleviation of drought and salt stress in plants: a critical review. Environmental Science and Pollution Research 24: 12700-12712.

Al Ismaili AM, Ahmed M, Al Busaidi A, Al Adawi S, Tandlich R, Al Amri M. (2017). Extended use of grey water for irrigating home gardens in an arid environment. Environmental Science and Pollution Research 24(1): 13650–13658.

Al-Ismaily S. (2011). Effect of manure amendments with varying C:N ratios on N mineralization. Project Final Report, Internal Grant, Sultan Qaboos University, Oman.

Al-Ismaily S, Al-Yahyai RA, Al-Rawahy SA. (2014). Mixed fertilizer can improve fruit yield and quality of field-grown tomatoes irrigated with saline water. Journal of Plant Nutrition 37: 1981-1996.

Al Jabri, M. (2003). Production of Mango in the Sultanate of Oman. Directorate General of Development Agriculture Information Office, Ministry of Agriculture and Fisheries. Sultanate of Oman (in Arabic).

Al-Kindi I. (2019). Effect of ash and biochar from *Maerua crassifolia* and *Saccharum kaikaiense* feedstock on plant growth and soil properties. Supervised undergraduate research report, Sultan Qaboos University. 22 pp.

Al-Lawati AH, Al-Saady N, Al-Khafaji HC, Patzelt A, Phillips J, Maxted N, Al-Bulushi AH, AL-Mabali D, Al-Naabi AS, Al-Busaidi KA, Al-Karusi M, Al-Shukali MS, Al-Jabri AA, Al-Nahani HM. (2017). Socioeconomic Plants Conservation Strategy for the Sultanate of Oman. Oman Animal and Plant Genetic Resources Center, the Research Council of the Sultanate of Oman, Muscat, Sultanate of Oman.

Al-Maskri A, Janke R, Al-Busaidi W, Khan M. (2018). Effects of *Sesbania aculeata* Pers. on soil properties. Aspects of Applied Biology 140, Soil improvement: Impact of Management Practices on Soil Function and Quality, pp.71-76. The Sophi Taylor Conference Centre. National Institute of Agricultural Botany, Cambridge, UK, on 16 October 2018. Association of Applied Biologist.

Al-Mayahi A, Al-Ismaily S, Gibreel T, Kacimov A, Al-Maktoumi A. (2019). Home gardening in Muscat, Oman: Gardener's practices, perceptions and motivations. Urban Forestry & Urban Greening 38: 286-294.

Al-Mazroui SS, Al-Sadi AM. (2016). 454 Pyrosequencing and direct plating reveal high fungal diversity and dominance by saprophytic species in organic compost. International Journal of Agricultural Biology 18: 98-102.

Al-Mazroui SS, Al-Sadi AM. (2015). Highly variable fungal diversity and the occurrence of potentially plant pathogenic fungi in potting media, organic fertilizers and composts originating from 14 countries. Journal of Plant Pathology 97: 529-534.

Alotaibi KD, Schoenau JJ. (2019). Addition of biochar to a sandy desert soil: effect on crop growth, water retention and selected properties. Agronomy 9: 1-14 (Article 3217).

Al-Rawahy SA, Al-Dhuhli HS, Prathapar SA, AbdelRahman H. (2011). Mulching material impact on yield, soil moisture and salinity in saline-irrigated sorghum plots. International Journal of Agricultural Research 6: 75-81.

Al-Sadi AM, Al-Oweisi FA, Edwards SG, Al-Nadabi H, Al-Fahdi AM. (2015a). Genetic analysis reveals diversity and genetic relationship among Trichoderma isolates from potting media, cultivated soil and uncultivated soil. BMC Microbiology 15: 147.

Al-Sadi AM, Al-Mazroui SS, Phillips AJL. (2015b). Evaluation of culture-based techniques and 454 pyrosequencing for the analysis of fungal diversity in potting media and organic fertilizers. Journal of Applied Microbiology 119: 500-509.

Al Said FA, Al-Yahyai RA, Opara UL. (2013). Traditional cultivation of pomegranate in Oman. Proc. 2nd All Africa Horticulture Congress. Eds: K. Hannweg and M. Penter. Acta Hort. 2007, ISHS.

Al Salmi MR. (2020). The technical efficiency of leading vegetable crops in Oman and their contribution to economic diversification. PhD Thesis, Sultan Qaboos University. Muscat, Oman, pp. 188

Al Toobi M. (2018). The efficacy of silica and biochar amendments on cucumber growth under saline conditions. MSc Thesis, Sultan Qaboos University, Muscat, Oman. pp 64.

Al-Toubi A. (2015). Society's awareness about organic farming and characterization of local composts and their effects on soil and cucumber growth in Oman. MS Thesis, Sultan Qaboos University, pp. 55.

Al-Yahya'ei MN, Oehl F, Vallino M, Lumini E, Redecker D, Wiemken A, Bonfante P. (2011). Unique arbuscular mycorrhizal fungal communities uncovered in date palm plantations and surrounding desert habitats of Southern Arabia. Mycorrhiza 21: 195-209.

Al-Yahyai R, Khan M. (2015). Date palm status and perspective in Oman. in Date Palm Genetic Resources and Utilization: Volume 2: Asia and Europe. J.M. Al Khayri et al. (eds). Springer Science+Busines Media Dordrecht.

Al Yahyai R, Al Hashmi K. (2017). Agroecology of traditional date palm plantations in Oman. 2nd National Conference on Agriculture & Fisheries Research, Sultan Qaboos University, Sultanate of Oman. 3-4 April 2017.

Al Zadjali S, Morse S, Chenoweth J, Deadman M. (2014). Factors determining pesticide use practices by farmers in the Sultanate of Oman. Science of the Total Environment 476-477: 505-512.

Anon. (2011). Annual Agricultural Calendar. 2nd edition. Directorate General of Development Agriculture Information Office, Ministry of Agriculture and Fisheries. Sultanate of Oman. Arabic.

Anon. (2013a). Determination of optimum fertilization of Omani garlic. MAF Annual Report. Directorate General of Agriculture & Livestock Research. p. 30.

Anon. (2013b). Effect of Kala compost on the performance of tomato crop in the field. MAF Annual Report. Directorate General of Agriculture & Livestock Research. p. 30.

Anon. (2013c). Effect of different levels of N.P.K. on the forage yield of sorghum grown under treated wastewater irrigation. MAF Annual Report. Directorate General of Agriculture & Livestock Research. p. 31.

Anon. (2018). Evaluation of growth and production of 'Khlalas' variety under different levels of nitrogen using organic matter. MAF Annual Report. Directorate General of Agriculture & Livestock Research. p 45.

Aon M, Khalid M, Sahir ZA, Ahmad R. (2015). Low temperature produced citrus peel and green waste biochar improved maize growth and nutrient uptake, and chemical properties of calcareous soil. Pakistan Journal of Agricultural Science. 52: 627-636.

Araújo ASF, Melo WJ. (2010). Soil microbial biomass in organic farming system. Ciência Rural 40(11): 2419-2426.

Banerjee S, Walder F, Büchi L, Meyer M, Held AY, Gattinger A, Keller T, Charles, R, Van Der Heijden MG. (2019). Agricultural intensification reduces microbial network complexity and the abundance of keystone taxa in roots. The ISME Journal 13(7): 1722-1736.

Barker AV, (2010). Science and Technology of Organic Farming, CRC Press, Boca Raton, FL, US.

Bassil KL, Vakil C, Sanborn M, Cole DC, Kaur JS, Kerr KJ. (2007). Cancer health effects of pesticides – systematic review. Canadian Family Physician 53: 1704-1711.

Baudry J, Assmann KE, Touvier M, Alles B, Seconda L, Latino-Martel P, Ezzedine K, Galan P, Herchberg S, Lairon D, Kesse-Guyot E. (2018). Association of frequency of organic food consumption with cancer risk. Findings from the NutriNet-Sante prospective cohort study. JAMA Internal Medicine 178(12): 1597–1606.

Bradbury KE, Balkwill A, Spencer EA, Roddam AW, Reeves GK, Green J, Key TJ, Beral V, Pirie K. (2014). Organic food consumption and the incidence of cancer in a large prospective study of women in the United Kingdom. British Journal of Cancer 110: 2321-2316.

Brinton WF. (2001). An international look at compost standards. Biocycle International 4: 74-76.

Castillo AG, Puig CG, Cumagun CJR. (2019). Non-synergistic effect of *Trichoderma haraianum* and *Glomus* spp. in reducing infection of *Fusariuim* wilt in banana. Pathogens 8: 1-8.

Chen Y, Camps-Arbestain M, Shen Q, Singh B, Cayuela ML. (2018). The long-term role of organic amendments in building soil nutrient fertility: a meta-analysis and review. Nutrient Cycling in Agroecosystems 111: 103-125.

Cookson P. (1996). Soil research in Oman: Opportunities and priorities. Agricultural Sciences 1: 35-32.

Curl C, Fenske R, Elgethun K. (2003). Organophosphorus pesticide exposure of urban and suburban preschool children with organic and conventional diets. Environmental Health Perspectives 111: 377-382.

Daffonchio D, Hirt H, Berg G. (2015). Plant-microbe interactions and water management in arid and saline soils, Principles of Plant-Microbe Interactions. Springer, New York. p. 265-276.

Dangour AD, Dodhia SK, Hayter A, Allen E, Lock K, Uauy R. (2009). Nutritional quality of organic foods: a systematic review. American Journal of Clinical Nutrition 90: 680-685.

Das, P., Chatterjee, S., Behera, B.K., Dangar, T.K., Das, B.K., Mohapatra, T., (2019). Isolation and characterization of marine bacteria from East Coast of India: functional screening for salt stress tolerance. Heliyon 5(6), e01869.

Delate, K., Cambardella, C., Chase, C., Turnbull, R., (2015). A review of long-term organic comparison trials in the U.S. Sustainable Agriculture Research, Canadian Center of Science and Education 4: 5-14.

Diacono, M., Montemurro, F., (2015). Effectiveness of organic wastes as fertilizers and amendments in salt-affected soils. Agriculture 5:221-230.

De Vries FT, Liiri, M.E., Bjørnlund, L., Bowker, M.A., Christensen, S., Setälä, H.M., Bardgett, R.D., (2012) Land use alters the resistance and resilience of soil food webs to drought. Nature Climate Change 2: 276-280.

Doran, J.W. and Parkin, T.B., (2015). Defining and Assessing Soil Quality. In Defining Soil Quality for a Sustainable Environment (eds J. Doran, D. Coleman, D. Bezdicek and B. Stewart). doi:10.2136/sssaspecpub35.c1

Drinkwater LE, Wagoner P, Sarrantonio M. (1998). Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396: 262-265.

Drinkwater, L.E. (2009). Ecological knowledge: Foundation for sustainable organic agriculture. In Francis, Charles (ed). Organic Farming: The Ecological System. Agronomy Monograph 54. American Society of Agronomy.

Edmeades, D.C. (2003). The long-term effects of manures and fertilizers on soil productivity and quality: a review. Nutrient Cycling in Agroecosystems 66:165-180.

El-Fouly, M.M. Shaban, M.M., (1999). The nutritional status of some horticultural crops in Salalah region, Sultanate of Oman. Agricultural Sciences 4:47-52.

Francis, Charles (ed). (2009). Organic Farming: The Ecological System. Agronomy Monograph 54. American Society of Agronomy.

Frew, A. (2019). Arbuscular mycorrhizal fungal diversity increases growth and phosphorus uptake in C3 and C4 plants. Soil Biology and Biochemistry. 135:248-250.

Gaube, H. Gangler, A., (eds). (2012). Transformation Processes in Oasis Settlements of Oman. Al Roya Press and Publishing House. Muscat, Oman.

Ghabishi, A. (2005). Field and Forage Crops in the Sultanate of Oman. Directorate General of Development Agriculture Information Office, Ministry of Agriculture and Fisheries. Sultanate of Oman. Arabic.

Halo, B. A., Al-Yahyai, R. A., Al-Sadi, A. M., (2020). An endophytic *Talaromyces omanensis* enhances reproductive, physiological and anatomical characteristics of drought-stressed tomato. Journal of Plant Physiology, 153163.

Hamed, J. Habees, M., (2014). Coconut Trees in the Sultanate of Oman. Information Office, Ministry of Agriculture and Fisheries. Sultanate of Oman. Arabic.

Hamel, C., (1996). Prospects and problems pertaining to the management of arbuscular mycorrhizae in agriculture. Agriculture, Ecosystems and Environment 60:197-210.

Harman, G.E., Obregon, M.A., Samuels, G.J., Lorito, M., (2010). Changing models for commercialization and implementation of biocontrol in the developed and developing world. 94:928-939

Hartmann, M., Khalil, S., Bernet, T., Ruhland, F., Al Ghamdi, A., (2012). Organic Agriculture in Saudi Arabia. Sector Study, (GIZ/MoA Organic Farming Project.) Deutsche Geseltischafl fur Internationale Zusammenarbeit BIZ, Saudi Organic Farming Association, Research Institute or Organic Agriculture (FiBL) & Ministry of Agriculture of Saudi Arabia (MoA), Riyadh, KSA.

Hartmann, M., Frey, B., Mayer, J., Mäder, P., Widmer, F., (2015). Distinct soil microbial diversity under long-term organic and conventional farming. The ISME journal 9(5), 1177-1194.

Hoitink, H.A.J., Madden, L.V., Dorrance, A.E., (2006). Systemic resistance induced by Trichoderma spp.: Interactions between the host, the pathogen, the biocontrol agent, and soil organic matter quality. Phytopathology 96:186-189.

Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A. M., Solaiman, Z. M., Alghamdi, S. S., ... & Siddique, K. H. (2017). Biochar for crop production: potential benefits and risks. Journal of Soils and Sediments, 17(3), 685-716.

Hussain, M.I., Muscolo, A., Farooq, M., Ahmad, W., (2019). Sustainable use and management of non-conventional water resources for rehabilitation of marginal lands in arid and semiarid environments. Agricultural Water Management 221:462-476.

Hussain, N. (2005). Strategic plan for combating water and soil salinity in Sultanate of Oman for 2005-2015. Ministry of Agriculture and Fisheries, Oman, 117.

Ingold, M., Dietz, H., Sradnick, A., Joergensen, R.G., Schlecht, E., Buerkert, A., (2015). Effects of activated charcoal and quebracho tannin amendments on soil properties in irrigated organic vegetable production under arid subtropical conditions. Biology and Fertility of Soils, 51, 367-377.

Jaizme-Vega, M.C. Pinochet, J., (1997). Growth response of banana to three mycorrhizal fungi in *Pratylenchus goodeyi* infested soil. Nematropica. 27(1):

Jefwa, J.M., Kahangi, W., Losenge, T., Mung'atu, J., Ngului, W., Ichami, S.M., Sanginga, N., Vanluawe, B., (2012). Arbuscular mycorrhizal fungi in the rhizosphere of banana and plantain and the growth of tissue culture cultivars. Agriculture, Ecosystems and Environment. 157:24-31.

Jordan, G., Predotova, M., Ingold, M., Goenster, S., Dietz, H., Joergensen, R.G., Buerkert, A., (2015). Effects of activated charcoal and tannin added to compost and to soil on carbon dioxide, nitrous oxide and ammonia volatilization. J. Plant Nutr. Soil Sci. 178:218-228.

Kazeeroni, E.A. Al-Sadi, A.M., (2016). 454-Pyrosequencing reveals variable fungal diversity across farming systems. Front. Plant Sci. 7:314. doi: 10.3389/fpls.2016.00314

Khaliq, S., Ahmed, M., Al Wardy, M., Al Busaidi, A., Choudri, B.S., (2017a). Wastewater and sludge management and research in Oman: An Overview. Journal of the Air and Waste Management Association. 67(3):267-278.

Khaliq, S.J., A. Al Busaidi, M. Ahmed, M. Al Wardy, H. Agrama and B.S. Choudri. (2017b). The effect of municipal sewage sludge on the quality of soil and crops. Int. J. Recycl. Org. Waste Agricult. DOI 10.1007/s40093-017-0176-4

Khan, M., Al-Busaidi, W., Janke, R., Al-Kindi, I., (2018a). Use of soil amendments in sustainable organic farming systems. Bioscience Research, 15 (4) 4128-4135. https://www.isisn.org/BR15(4)2018/4128-4135-15(4)2018BR18-355.pdf

Khan, M., Al-Busaidi, W., Janke, R., Al-Kindi, I., (2018b). Use of novel soil amendments in sustainable organic farming system. Soil Improvement: Impact of Management Practices on Soil Function and Quality. The Sophi Taylor Conference Centre. National Institute of Agricultural Botany, Cambridge, UK, on 16 October 2018. Association of Applied Biologist.

Knewtson, S.J.B., Kirkham, M.B., Janke, R.R., Murray, L.W., Carey, E.E., (2012). Soil quality after eight years under high tunnels. HortScience 47:1630-1633.

Liao, J., Liang, Y., Huang, D., (2018). Organic farming improves soil microbial abundance and diversity under greenhouse condition: A case study in Shanghai (Eastern China). Sustainability 10(10), 3825.

Liebhardt, W.C., Andrews, R.W., Culik, M.N., Harwood, R.R., Janke, R.R., Radke, J.K., Riegerschartz, L.L., (1989). Crop production during conversion from conventional to low-input methods. Agron. J. 81:150-159.

Lockeretz, W. (ed). (2007). Organic Farming: An International History. CAB International, Wallingford, UK, 2007. ISBN: 978-0-85199-833-6, 320 pp.

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., Gattinger, A., (2017). Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. PLoS One 12(7), e0180442.

Lozupone, C., Knight, R., (2007). Global patterns in bacterial diversity. Proc. Natl. Acad. Sci. 104, 11436-11440.

Lu, C., Toepel, K., Irish, R., Fenske, R., Barr, D., Bravo, R., (2006). Organic diets significantly lower children's dietary exposure to organophosphorus pesticides. Environ. Health Persepct. 114:260-263.

Lupatini, M., Korthals, G.W., de Hollander, M., Janssens, T.K., Kuramae, E.E., (2017). Soil microbiome is more heterogeneous in organic than in conventional farming system. Frontiers in microbiology 7, 2064.

Maharachchikumbura, S.S.N., Al Sadi, A.M., Al Kharousi, M., Al Saady, N., Hyde, K.D., (2016). A checklist of fungi in Oman. Phytotaxa, 273(4), 219-261.

Mbaga, M. (2014). The prospects of sustainable desert agriculture to improve food security in Oman. Consilience: The Journal of Sustainable Development. 13:114-129.

MAF (Ministry of Agriculture and Fisheries). (1990). Sultanate of Oman General Soils Map. 110 pp. Muscat, Oman.

MAF (Ministry of Agriculture and Fisheries). (1992). Salalah Integrated Study: Soil Survey and Land Classification Project OMA/87/0111. Directorate General of Agricultural Research. Sultanate of Oman.

MAF (Ministry of Agriculture and Fisheries). (1993a). South Batinah Integrated Study Vol. 1, 2, 3 &4. Land Resources, Soil Survey and Land Classification Project OMA/87/011/. Muscat, Oman.

MAF (Ministry of Agriculture and Fisheries). (1993b). Salalah Integrated Study Vol. 1, 2, 3 &4. Land Resources, Soil Survey and Land Classification Project. Sultanate of Oman. Muscat, Oman.

MAF (Ministry of Agriculture and Fisheries). (1993c). North Batinah Integrated Study Vol. 1,2,3,4. Land Resources, Soil Survey and Land Classification Project. Sultanate of Oman. Muscat, Oman.

MAF (Ministry of Agriculture and Fisheries). (1997a). Integrated study of North: Sohar. Directorate General of Agricultural Research. Sultanate of Oman.

MAF (Ministry of Agriculture and Fisheries). (1997b). Integrated study of North: Liwa. Directorate General of Agricultural Research. Sultanate of Oman.

MAF (Ministry of Agriculture and Fisheries). (1997c). Integrated study of North: Shinas. Directorate General of Agricultural Research. Sultanate of Oman.

MAF (Ministry of Agriculture and Fisheries). (2015). Agricultural Census 2012/2013. 252 pp. Muscat, Oman.

Maynard, D.N. Hochmuth, G.J., (2007). Knott's Handbook for Vegetable Growers, 5th Edition. John Wiley and Sons, Inc.

Menezes-Blackburn, D., Inostroza, N.G., Gianfreda, L., Greiner, R., Mora, M.L., Jorquera, M.A., (2016). Phytase-producing *Bacillus* sp. inoculation increases phosphorus availability in cattle manure. Journal of Soil Science and Plant Nutrition 16: 200-210

Ministry of Regional Municipalities and Water Resource. (2013). Water Balance Computation for the Sultanate of Oman. Final Report – Executive Summary. Mott MacDonald.

Moradi, A., Tahmourespour, A., Hoodaji, M., Khorsandi, F., (2011). Effect of salinity on free living-diazotroph and total bacterial populations of two saline soils. Afr. 5(2), 144-148.

National Water Resources Master Plan. (1999). Sultanate of Oman.

O'Brien, F.J.M., Almaraz, M., Foster, M., Hill, A., Huber, D., King, E., Langford, H., Lowe, M.-A., Mickan, B.S., Miller, V., (2019). Soil salinity and pH drive soil bacterial community composition and diversity along a lateritic slope in the Avon River Critical Zone Observatory, Western Australia. Front. Microb. 10:1486.

Oo, A.N., Iwai, C.B., Saenjan, P., (2015). Soil properties and maize growth in saline and nonsaline soils using cassava-industrial waste compost and vermicompost with or without earthworms. Land Degradation & Development 26:300-310.

Ortas I., (2012). Mycorrhiza in citrus: Growth and nutrition. In: Srivastava A. (eds) Advances in Citrus Nutrition. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-4171-3_23

Ouni, Y., Lakhdar, A., Scelza, R., Scotti, R., Abdelly, C., Barhoumi, Z., Rao, M.A., (2013). Effects of two composts and two grasses on microbial biomass and biological activity in a salt-affected soil. Ecological Engineering 60:363-369.

Palansooriya KN, Wong JTF, Hashimoto Y, Huang L, Rinklebe J, Chang SX, Bolan N, Wang H, Ok YS. (2019). Response of microbial communities to biochar-amended soils: a critical review. Biochar 1: 3-32.

Prathapar SA, Khan M, Mbaga MD. (2014). The potential of transforming Salalah into Oman's vegetables basket. S.A. Shahid and M. Ahmed (eds.), Environmental Cost and Face of Agriculture in the Gulf Cooperation Council Countries: Fostering Agriculture in the Context of Climate Change, Gulf Research Centre Cambridge.

Price TD, Gebauer A, eds. (1996). Last Hunters – First Farmers: New Perspectives on the Prehistoric Transition to Agriculture.

Rietz D, Haynes R. (2003). Effects of irrigation-induced salinity and sodicity on soil microbial activity. Soil Biology and Biochemistry 35(6): 845-854.

Rubio MB, Hermosa R, Vicente R, Gómez-Acosta FA, Morcuende R, Monte E, Bettiol W. (2017). The combination of *Trichoderma harzianum* and chemical fertilization leads to the deregulation of phytohormone networking, preventing the adaptive responses of tomato plants to salt stress. Frontiers in Plant Science 8: 294.

Sanborn M, Kerr KJ, Sanin LH, Cole DC, Bassil KL, Vakil C. (2007). Non-cancer health effects of pesticides. Systematic review and implications for family doctors. Canadian Family Physician 53: 1712-1720.

Schrama M, de Haan JJ, Kroonen M, Verstegen H, Van der Putten, WH. (2018). Crop yield gap and stability in organic and conventional farming systems. Agriculture, Ecosystems and Environment 256: 123-130.

Shaharoona, B., Al Ismaily, S., Al Mayahi, A., Al Harraisi, N.,Al Kindi, R., Al Sulaimi, A., Al Busaidi, H., Al Abri, M., (2019). The role of urbanization in soil and groundwater contamination by heavy metals and pathogenic bacteria: A case study from Oman. Heliyon 5.

Siegfried K, Dietz H, Schlecht E, Buerkert A. (2011). Nutrient and carbon balances in organic vegetable production on an irrigated, sandy soil in northern Oman. Journal of Plant Nutrition and Soil Science 174: 678-689.

Smith-Spangler C, Brandeau M, Hunter G, Bavinger J, Pearson M, Eschbach P, Sundaram V, Liu H, Schrimer P, Stave C, Olkin I, Bravata DM. (2012). Are organic foods safer or healthier than conventional alternatives? A systematic review. Annals of Internal Medicine 157: 1539-3704

Symanczik S, Błaszkowski J, Koegel S, Boller T, Wiemken A, Al-Yahya'Ei MN. (2014a). Isolation and identification of desert habituated arbuscular mycorrhizal fungi newly reported from the Arabian Peninsula. Journal of Arid Land 6: 488-497.

Symanczik S, Błaszkowski J, Chwat G, Boller T, Wiemken A, Al-Yahya'ei MN. (2014b). Three new species of arbuscular mycorrhizal fungi discovered at one location in a desert of Oman: Diversispora omaniana, Septoglomus nakheelum and Rhizophagus arabicus. Mycologia 106(2): 243-259.

Symanczik S, Courty PE, Boller T, Wiemken A, Al-Yahya'ei MN. (2015). Impact of water regimes on an experimental community of four desert arbuscular mycorrhizal fungal (AMF) species, as affected by the introduction of a non-native AMF species. Mycorrhiza 25: 639-647.

Torsvik V, Øvreås L. (2002). Microbial diversity and function in soil: from genes to ecosystems. Current Opinion in Microbiology 5: 240-245.

Tsiknia M, Paranychianakis NV, Varouchakis EA, Moraetis D, Nikolaidis NP. (2014). Environmental drivers of soil microbial community distribution at the Koiliaris Critical Zone Observatory. FEMS Microbiology Ecology 90: 139-152.

Venkateswarlu B. (2008). Role of biofertilizers in organic farming. In Organic Farming in Rainfed Agriculture - Opportunities and Constraints. Central Research Institute for Dryland Agriculture. (eds) Venkateswarlu, B. S.S. Balloli and Y.S. Ramakrishna, Hyderabad. 185 pp.

Wahaibi NSA, Hussain N, Rawah AA. (2007). Mulching for sustainable use of saline water to grow tomato in Sultanate of Oman. Science International (Lahore) 19: 79-81.

Waller JM, Bridge J. (1978). Plant Diseases and Nematodes in the Sultanate of Oman. PANS 24(3): 313-326.

Wasserstrom H, Kublik S, Wasserstrom R, Schulz S, Schloter M, Steinberger Y. (2017). Bacterial community composition in costal dunes of the Mediterranean along a gradient from the seashore to the inland. Scientific Reports 7: 1-7.

Willer H, Lernoud J. (eds). (2019). The World of Organic Agriculture: Statistics and Emerging Trends. FiBL-IFOAM Report. Organics International, Bonn.

Xing J, Wang H, Brookes PC, Salles JF, Xu J. (2019). Soil pH and microbial diversity constrain the survival of *E. coli* in soil. Soil Biology and Biochemistry 128: 139-149.

Yadav SK, Soni R, Rajput AS. (2018). Role of microbes in organic farming for sustainable agro-ecosystem. In: Panpatte D., Jhala Y., Shelat H., V. R. (Eds.), Microorganisms for green revolution. Springer, Singapore, pp. 241-252.

Yaish MW, Al-Harrasi I, Alansari AS, Al-Yahyai R, Glick BR. (2016). The use of high throughput DNA sequence analysis to assess the endophytic microbiome of date palm roots grown under different levels of salt stress. International Microbiology 19: 143-155.

Zafar-ul-Hye M, Danish S, Abbas M, Ahmad M, Munir TM. (2019). ACC deaminase producing PGPR *Bacillus amyloliquefaciens* and *Agrobacterium fabrum along* with biochar improve wheat productivity under drought stress. Agronomy 9: 1-16.

Zarb J, Ghorbani R, Koocheki A, Leifert C. (2005). The importance of microorganisms in organic agriculture. Outlooks on Pest Management 16: 52-55.

Zhang K, Shi Y, Cui X, Yue P, Li K, Liu X, Tripathi BM, Chu H. (2019). Salinity is a key determinant for soil microbial communities in a desert ecosystem. MSystems 4(1): 1-11.

Zhao X, Carey EE, Wang W, Rajashekar CB. (2006). Does organic production enhance phytochemical content of fruit and vegetables? Current knowledge and prospects for research. HortTechnology 16: 449-456.

Zong Y, Xiao Q, Lu S. (2016). Acidity, water retention and mechanical physical quality of a strongly acidic ultisol amended with biochars derived from different feed stocks. Journal of Soils and Sediments 16: 177-190.