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A Field Trial using Modified Alumina Refinery Residue to Beneficiate Composting at a Dairy Farm in Saudi Arabia

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Abstract – **Evidence suggests that alumina refinery residue, a byproduct of extracting alumina from bauxite, has properties which are beneficial to agriculture in general and to composting in particular. These contributions include increased moisture retention properties of soil and improved crop production. However, little evidence is available to confirm this claim in relation to Saudi Arabia or other Gulf States. This study therefore sought to investigate whether the addition of this type of residue to different dairy farm waste streams prior to composting had a beneficial effect on temperature and time to maturity of compost. Pure manure, manure plus bedding sand, leftover feed, and sludge from an on-site settling basin at a dairy farm in Al-Hofuf, Saudi Arabia were chosen as the four primary sources of organic matter for this large-scale field trial conducted during the autumn months of October to December. Results indicate that the addition of alumina refinery residue had no significant impact on the composting process, although minor benefits consistent with other research findings that could be attributed to the residue were observed. In this trial, differing beneficial results were more dependent on whether the compost was turned on a weekly or bi-weekly basis, and some standard measures were effected as a result of the trial. Both six- and 12-week stability and maturity data are presented.**

Keywords – **Composting, Dairy Farm Waste, Cow Manure, Alumina Refinery Residue, Saudi Arabia.**

I. INTRODUCTION

In the last five to ten years, the rate and volume of residential and industrial composting in Saudi Arabia have increased significantly. While restricted by factors such as clean water supply and availability of carbonaceous green waste, composting is seen as a vital part of an increased recycling and sustainabilityeffort in the Kingdom. This trend is also reflected in the growth of a viable organic agricultural industry in Saudi Arabia, which in 2012 included 78 farms with 16,400 ha under cultivation in a global market which saw 16 million ha of organic agriculture under cultivation and $13 billion in sales in 2000 grow to 58 million ha under cultivation and $35 billion in sales by 2010 [1]. Hartmann et al. report that a further 2,200 ha in Saudi Arabia were undergoing conversion from non-organic to organic farming in 2012 [1].

However, Al-Turkimaintainsthe stability (i.e.,the resistance of compost to degradation) and maturity (i.e., the fitness of compost for land application and plant growth potential) of commercial compost remain questionable in Saudi Arabia, with 64% of 14 compost samples exceeding the upper limit of acceptable electrical conductivity (EC), 36% exceeding the optimal carbon-to-nitrogen (C/N) ratio of 25:1, 71% exceeding the maximum value for nitrification, 64% exhibiting signs of phytotoxicity, and three samples containing either faecal coliform, salmonella or staphylococci at concentrations above regulatory limits [2].For these reasons, a number of industry observers have pointed out there is a growing need for improved quality control standards for industrial composting operations in Saudi Arabia[1, 2, 3]; Alzaydi et al. in particular note the general paucity of reliable data on composting quality and practices in the Kingdom [3].

While data on methods and quality outcomes are limited, researchers have begun considering many unique approaches to the practice of composting in Saudi Arabia. For example, Alkoaik et al. evaluated the effectiveness of a bioreactor to compost date palm residues mixed with chicken manure and found that organic matter (OM), organic carbon (OC), C/N ratio, temperature and moisture contents of various mixing rates resulted in the production of suitable compost outcomes [4]. Similarly, Al-Bharakah et al. assessed decomposition rates of three types of green waste (i.e., dates trees, olive trees and maize), mixed with animal manure (i.e., sheep manure) with fiveinoculated microorganisms or so-called “organic activators” (i.e., *Streptomycsaurefaciens*, *Trichoderma viridie*, *T. harzianum*, *Bacillicus subtilis*, and *B. licheniformis*) at four different addition rates using standard windrows at a large-scale project in the El-Jouf region [5]. Al-Bharakah et al. found that temperature could be effectively monitored according to three standard phases of change during the 24-hour cycle and noted that all compost blends reached maturity by the twelfth week, bacterial counts reached their apex by the sixth week and decreased to stability by the seventeenth week, coliform counts reached zero by the sixth week, and that other physicochemical changes indicative of stability, such as pH, EC, OM, OC and C/N ratio, were achieved by the thirteenth week [5].

Sadik et al. conducted one of the largest composting trials at Al Kalidhiah farm in Riyadh [6]. This study investigated a variety of agricultural and animal waste byproducts (including quail, goat and sheep manure, and date, citrus and olive tree green waste), composed of compost biopiles with and without the addition of a biological activator composed of microorganisms, enzymes and yeast. The biopiles were turned every five days and were measured for variables such as temperature and moisture content. These researchers found that the biopiles with biological activator achieved the target 15:1 C/N ratio within 35 days (in comparison to the standard 68-180 days), and the resultant compost was free of salmonella, faecal coliform, total coliform, mycotoxins and heavy metals.

Elhindi evaluated the effects of applying compostto the growth rates, quality and chemical composition of common,or pot,marigolds (*Calendula officinalis*) in sandy soilusing surface and sub-surface drip irrigation [7]. He found that the sub-surface irrigationof marigolds was more effective across all three experimental parameters and resulted in greater soil fertility after harvesting.

In many studies on composting in Saudi Arabia, the use of date palm mulch (DPM) is the preferred organic carbon source [e,g., 4]; DPM is produced as a result of grinding the leaves, trunks and/or roots of date palms. Sadik et al. have noted the 23 million date palms which grow in Saudi Arabia have a life of more than 100 years and produce about 20 dry kg of organic matter per year [8]. According to Sadik et al., the use of DPM in composting is preferable over the practice of burning tree waste (which liberates carbon [C] and nitrogen [N] to the atmosphere) as anutrient source for plants because it results in decreasing water evaporation from the soil surface, helps control weed invasion, suppresses dust, helps prevent soil erosion by wind, and provides thermal soil stabilization by keeping it cool in hot weather and warm in cold weather.

Of relevance to the present study, Sadik et al. also showed that DPM mixed with cow manure using the standard "turned windrow" method resulted in the generation of a viable compost, which had improved concentrations of N, phosphorus (P) and potassium (K), had stable pH, EC and OM,had reduced concentrations of total dissolved solids (TDS), and was free of unpleasant odours, salmonella, faecal coliform and total coliform [8]. However, Sadik et al. noted that DPM displays a certain resistance to decomposition and that proper grinding of date palm waste is therefore important to produce a mulch which is fine enough for viable composting.

In addition to biological additives and organic activators, the use of inorganic chemical additives in composting for agricultural improvement in Saudi Arabia has not been fully investigated. For example, considerable research into the addition of alumina refinery residue (ARR), in both its unmodified and modified forms, to agricultural soils has been conducted in many countries based on the supposition that ARR might help agricultural soil retain moisture, neutralize acidity, bind heavy metals, and enhance the presence and retention of macro- and micronutrients in soil.

ARR is typically composed of iron (25-35%), aluminium (10-20%), sodium (3-10%), titanium (5-10%), silica (5-20%) and calcium (5-10%) in oxide, hydroxide and/or oxy-hydroxide states. ARR is composed of a complex cocktail of metals and minerals, including hematite (Fe_2O_3), beohmite (γ-AlOOH), gibbsite ($Al[OH]_3$), sodalite ($Na_4Al3Si_3O_{12}Cl$), anatase (TiO_2), aragonite ($CaCo_3$), brucite ($Mg[OH]_2$), diaspore (ß-$Al2O_3.H_2O$), ferrihydrite ($Fe_5O_7[OH].4H_2O$), gypsum ($CaSO_4.2H_2O$), hydrocalumite ($Ca_2Al[OH]_7.3H_2O$), hydrotalcite ($Mg_6Al_2CO_3[OH]_{16}.4H_2O$) and p-aluminohydrocalcite ($CaAl_2[CO_3]_2[OH]_4.3H_2O$). ARR may also contain heavy metals and metalloids, including arsenic (As), chromium (Cr), gallium (Ga), thorium (Th), uranium (U) and vanadium (V), although usually only in trace concentrations of a few parts per million up to 200 mg/kg. While the presence of radionuclides, such as lead (Pb), thorium (Th) and uranium (U), have raised concerns, these elements are almost always found in non-radioactive states [9].

About 50% of ARR is amorphous, with crystalline constituents composed mainly of goethite and hematite, quartz, and rutile, anatase and/or ilmenite; many minor remnant phases from the original bauxite ore (e.g., mica and boehmite) and newly formed species (e.g., natroalunite and noselite) may also be present. Upon contact with water, ARR imparts a pH of ±12.5, with elevated levels of EC at 1.0-16 dS/m; >80% of ARR particles are<10 micron [9, 10].

According to Snars et al. [11], the global research effort into ARR has concentrated on its potential effects in a number agricultural contexts, including P-retention of sandy soils to preventphosphate (PO_4) run-off to rivers and estuaries [12, 13, 14, 15], increasing yields of horticultural crops and pastures with and without the addition of N, P, and Kfertilisers [16, 17], and the so-called"liming"of acidic soils [16, 18].

Waddell et al.reported findings of glasshouse and laboratory trials using ARR to beneficiate compost [19]. Of particular interest to the present study, Waddell et al. investigated the impact of ARR on retaining soluble P in compost added to sandy soils and its impact on the growth of *Raphanussativas* or long scarlet radishes. Starting concentrations of 0.83% total P in the compost were detected, achieved as a result of ARR addition rates between 1-5% (on a w/w basis) to sandy soils. Results indicated that radish yields from crops grown in sandy soils amended with ARR-compost were significantly higher than a control soil with and without unamended compost, but yields were not as high as crops grown in sandy soils amended with composts containing other clay-like additives, including zeolite. However, Waddell et al. also reported that evidence suggests there was decreased P loss in soil and greater retention of P in radish roots when ARR addition rates increased, with P concentrations of 0.38% in roots and 0.24% in leaves 11 weeks after application. Waddell et al. also found that ARR significantly aided the retention of nitrogen in sandy soils [19].

Thiyagarajan et al. similarly studied to role of ARR and compost and its relation to manganese (Mn)-retention in sandy soils [20], and Anderson et al. investigated whether amending ARR sand (i.e., the course "sand" fraction of ARR, calleddesilication products by the alumina industry,which is between 10% and 50%) with ARR fines (i.e., the "fine" sand fraction) would improve its suitability as a growth medium. Anderson et al. found that the addition of ARR more than doubled plant-available water and increased extractable nutrient concentrations relative to unaltered sand, and increased extractable K, P, sulphur (S), magnesium (Mg) and boron (B) in the growth medium [21]. However, ARR treatments also increased both the EC and exchangeable sodium (Na) percentage of the growth medium.

This author has also reported on the use of a modified form of ARR in both composting and agriculture. Fergusson documented the application of modified alumina refinery residue (MARR), which had been modified using seawater to reduce total alkalinity caused by high concentrations of sodium [Na] and chloride Cl] in the original ARR, in a composting trial at a municipal council site in Queensland, Australia [10]. In that study, composting times to stability of biosolids and green waste were reduced from a standard 11-14 week composting period to seven weeks, the amount of carbonaceous green waste required for compost to reach maturity was reduced by 50%, and the averagebiopile temperature was increased from 60-67⁰C over seven weeks. Fergusson also reported that MARR has been used as a fertiliser supplementat a cotton farm in New South Wales, resulting in increased height, number of nodes, height:node ratio, fruiting factor, and nodes above white fruit of cotton [10].

This overview of composting in Saudi Arabia and the possible role ARR might play in it leads to the present study, which asks the followingresearch question: Do different turning schedules and the addition ofdifferent rates of MARRaugment the composting process and the properties of compost at a dairy farm in Saudi Arabia when compared to standard compost derived from cow manure?

II. METHOD

The site chosen for this study was located in Al-Hofuf in eastern Saudi Arabia. The dairy farm accommodates about 12,000 Friesen and Holstein cows and 3,000 replacement stock on about 450 ha of arable land. The farm generates about 4,900m^3 of pure cow manure per year (39,000m^3 total manure and bedding sand per year), plus various organic wastes, including leftover feed (4,000m^3 per year), such as hay and feed concentrates that are not consumed by cows and scraped from the feeding table before new feed is added, residues from an on-site wastewater treatment plant (WWTP), including dried primary sludge (which contains >10mm particulate matter), sludge from a primary settling basin and dried secondary sludge (for a total of 3,600m^3 per year), and a variety of on-site green wastes (1,200m^3 per year)consisting mostly of DPM and grass clippings. In total, the farm generates about 50,000m^3(or 34,000 tonnes) of organic residues each year, about 75% of which is composed of manure and bedding sand.

The field trial was conducted during the months of October through December, when daytime temperatures average 24⁰C and night-time temperatures average 13⁰C, with zero precipitation during these months and humidity at around 80%. Stormwater runoff (note, there were no rain events during this field trial) was controlled by diversion banks and below-ground pipes, with potential runoff being diverted to a settling and holding pond; a sediment trap was installed to intercept solids prior to entering the pond. Adequate buffers of more than 50 m were configured to protect surrounding dairy infrastructure; irrigation water sourced from a local bore was supplied to the field trial site by water tanker.

Table 1: Pre-trial analysis of potential waste streams to be used in the field trial.

Parameter (Unit)	Pure Manure	Manure and Bedding Sand	Leftover Feed	Primary Sludge	Primary Settling Basin Sludge	Secondary Sludge
Dry matter (%)	83	87	70	25	24	67
Moisture content (%)	17	13	30	75	76	33
pH	6.7	6.5	5.6	7.3	7.3	6.9
EC (dS/m)	15.6	13.9	12.8	1.6	4.2	13.4
Organic matter (%)[†]	19.5	17	89.5	80	54.5	52
Organic carbon (%)[‡]	11.5	10	52.6	47	32	31
Total nitrogen (%)	0.77	0.73	2.6	1.2	1.6	2.8
C/N ratio	15:1	14:1	20:1	38:1	20:1	11:1
Total phosphorus (%)	0.32	0.31	0.18	0.39	0.19	0.70
N/P ratio	1:0.4	1:0.4	1:0.1	1:0.3	1:0.1	1:0.25
Odour	3	2	1	4	3	3

[†]Determined by dry-ash method; [‡]Calculated by dividing organic matter by 1.7, with no correction forinorganic carbon content.

Analyses of these various waste streams, excluding green wastes, were conducted prior to the field trial; results from these analyses are shown in Table 1. These data show relatively low total nitrogen (TN) concentrations for both pure manure and manure and bedding sand wastes (cow manure typically contains about 1.5-2.0% TN, according to Pratt and Castellanos [22] and Eghbal [23]), with near-neutral pH of 6.6 and high EC averaging 14.7 dS/m. OM, OC and TN concentrations in leftover feed were markedly higher than in pure manure and manure and bedding sand, but with comparable pH and EC levels. Organic residues from the WWTP were distinctly different from pure manure, manure and bedding sand, and leftover feed.

Dried primary sludge and primary settling basin sludge had high moisture levels of around 75%, pH was near-neutral but EC was relatively low in the two primary sludges, but not in secondary sludge; of note also are the higher concentrations of OC and TN in all three WWTPsludges. Total nitrogenconcentrations ranged from 0.73% in manure and bedding sand to 2.6% in secondary waste sludge, but total phosphorus (TP) concentrations were relatively uniform across all six waste streams at between 0.18 to 0.70, which was in the standard range for dairy cow manure [23]; C/N ratios were significantly different in leftover feed and the two primary sludge types when compared to pure manure, manure andbedding sand, and dried secondary sludge.

Objectionable odours emanating from manure and sludgegenerated at dairy farms can impact local amenities, but typically malodours are not in concentrations which pose a risk to human health. Odours can be caused by the out-gassing of ammonia gas, hydrogen sulphide, trimethyl amine and dimethyl disulphide. In this field trial, concentrations of objectionable odour, while not isolated for their specific chemical composition, were assessed using a self-reporting instrument requiring three on-site dairy farm operators to rate odour of pre-composted feedstocks and post-composted biopileson a scale of 0-5, with “0” representing no discernible odour; “1” representing non-offensive, not unpleasant odour which was tolerable by all; “2” representing mild, unpleasant odour, which was tolerable by all; “3” representing unpleasant odour,which was tolerable to most; “4” representing offensive, highly unpleasant odour,which was tolerable to some; and “5” representing foul odour, which causes nausea in sensitive people and is intolerable to most. Feedstocks were rated between “1” for leftover feed to “4” for primary sludge.

Due to availability, the main feedstocks identified for this field trial were pure manure, manure andbedding sand, leftover feed, and primary settling basin sludge. On a compacted earth pad, these four feedstocks were mixed with other organic wastes in ratios presented in Table 2. Components were added and mixed using a front-end loader, and each composite mix was labelled biopile A, B or C.

Biopile A consisted of 126m^3 of pure manure (88% by volume), 15m^3 leftover feed (10% by volume) and 3.0m^3 green waste (2% by volume) for a total of 144 m^3, and biopile B consisted of 71m^3 of manure andbedding sand(49% by volume), 71m^3 leftover feed (49% by volume) and 3.0m^3 green waste (2% by volume) for a total of 145 m^3. Due to a reduced availability of primary settling basin sludge, biopile C consisted of 33m^3 of primary settling basin sludge (42% by volume), 33m^3 leftover feed (42% by volume), and 3.0m^3 green waste (4% by volume) to which a further 9.0 m^3 of primary sludge from the WWTP (12% by volume) was added for a total of 78 m^3.After the three biopiles were created but prior to composting, each biopile was analysed for moisture content, pH, EC, OM, OC, TN, C/N ratio, TP and N/P ratio; analytical data for each biopile are presented in Table 3. These data indicate the biopiles were relatively uniform in chemical and physical properties, although biopile C had a significantly lower EC than either biopile A or B, and biopile B had a significantly lower OM and

Table 2: Primary components and volumes of biopiles A, B and C.

Biopile Code	Components	Volume (m^3)	Volume %
A	Pure manure	126	88
	Leftover feed	15	10
	Green waste	3.0	2.0
	Total	144	100
B	Manure andbedding sand	71	49
	Leftover feed	71	49
	Green waste	3.0	2.0
	Total	145	100
C	Primary Settling Basin Sludge	33	42
	Leftover feed	33	42
	Green waste	3.0	4.0
	Primary sludge	9.0	12
	Total	78	100

Table 3: Pre-trial analysis of biopiles A, B and C prior to addition of MARR.

Parameter (Unit)	Biopile		
	A	B	C
Moisture content (%)	45	25	49
pH	6.9	7.6	7.5
EC (dS/m)	18.5	18.7	7.2
Organic matter (%)	27	18.7	34.5
Organic carbon (%)	15.9	11	20.3
Total nitrogen (%)	0.90	1.1	1.4
C/N ratio	14:1	12:1	15:1
Total phosphorus (%)	0.25	0.18	0.23
N/P ratio	1:0.3	1:0.2	1:0.2

OC percentage than either biopile A or C. In most other parameters, variation were insignificant. OC concentrations ranged from 11% to 20.3% and OM from 18.7% to 34.5%.

Tobiopiles A, B and C, MARR was added and mixed with a front-end loader. The MARR used in this trial was sourced from Queensland Alumina in Australia and shipped to Saudi Arabia for this field trial. The MARR had been previously rinsed with seawater, which resulted in a pH of 9.0and EC of 10.8 dS/m, and contained 34% Fe_2O_3, 18% ɤ-AlOOH, 13% $Al[OH]_3$, 18% $Na_4Al_3Si_3O_{12}Cl$, 8% quartz, 7% calcium minerals, and 2% magnesium minerals.

The MARR was added to each biopileon a volume-to-volume basis at three rates 0.5%, 1% and 1.5%, resulting in three sub-biopiles of each biopile, which were labelled A-1 (addition of 0.5% MARR), A-2 (addition of 1.0% MARR) and A-3 (addition of 1.5% MARR), B-1 (addition of 0.5% MARR), B-2 (addition of 1.0% MARR) and B-3 (addition of 1.5% MARR), and C-1 (addition of 0.5% MARR), C-2 (addition of 1.0% MARR) and C-3 (addition of 1.5% MARR). Biopiles A-1, A-2, A-3, B-1, B-2 and B-3 were then divided into two equal parts of approximately 24 m^3each (one for weekly and one for bi-weekly turning) to form 12 biopiles and labelled accordingly. Thus,biopile A-1-A was composed of 0.5% MARR and would be turned on a weekly basis, A-1-B was composed of 0.5% MARR and would be turned on a bi-weekly basis (i.e., every two weeks), and so on through all 12 biopiles.

Due to the limited availability of the primary settling basin sludge used in biopile C, sub-biopiles C-1, C-2 and C-3, which each consisted of approximately 26 m^3 of total waste, could not be subdivided into weekly and bi-weekly turning schedules and were therefore turned on a bi-weeklybasis only. The labelling of the final 15 biopiles, MARR addition rates, and turning schedules for the field trial are presented in Table 4.

Table 4: Addition rates of MARR andturning schedule with codes ofthe final 15 biopiles.

Biopile	Code	MARR	Code	Turning
A	A-1	0.5%	A-1-A	Weekly
			A-1-B	Bi-weekly
	A-2	1.0%	A-2-A	Weekly
			A-2-B	Bi-weekly
	A-3	1.5%	A-3-A	Weekly
			A-3-B	Bi-weekly
B	B-1	0.5%	B-1-A	Weekly
			B-1-B	Bi-weekly
	B-2	1.0%	B-2-A	Weekly
			B-2-B	Bi-weekly
	B-3	1.5%	B-3-A	Weekly
			B-3-B	Bi-weekly
C	C-1	0.5%	—	Bi-weekly
	C-2	1.0%	—	Bi-weekly
	C-3	1.5%	—	Bi-weekly

Having established the biopiles, temperature and moisture levels were monitored and recorded on a daily basis; temperatures at approximately 80 cm below the surface of each biopile were measured with a hand-held temperature probe (target average temperatures for compost are 50^0C, with a minimum of three consecutive days greater than 55^0C, although some jurisdictions require temperatures above 65^0C for at least three days). A hand-held soil moisture probe was used to determine volumetric moisture content (% by volume) at 10-20 cm below the surface and to calculate weekly water requirements; these measurements were supplemented by the so-called “hand squeeze” or wet-rag test[24].

In the hand squeeze test, a handful of compost is sampled and squeezed into a ball by forming a fist; as a result, one or two drops of water may fall from the ball and, on release, the ball should expand but remain intact. In such circumstances, the compost is composed of approximately 50% moisture. If more than a few drops fall from the ball on squeezing, the compost is too wet; in conditions of greater than 60% moisture, degradation will be slowed, malodours will be formed, and supernatant liquor may be produced. The percentage of water required in composting (i.e., to maintain moisture content at between 40-60%) is calculated as the percentage moisture at the desired condition less the current percentage moisture. The percentage of water required is multiplied by the mass of material in the pile to give the mass of water to be added.

Table 5 presents the field trial schedule and addition rates of volumetric water. In Week 1, 667 L of water were added to biopiles A-1-A, A-2-A, A-3-A, B-1-A, B-2-A and B-3-A (approximately 111 L/biopile); in Week 2, 720 L of water were added to biopiles A-1-B, A-2-B, A-3-B, B-1-B, B-2-B, B-3-B, C-1, C-2 and C-3 (approximately 80 L/biopile) and 80 L of water were added to biopiles A-1-A, A-2-A, A-3-A, B-1-A, B-2-A and B-3-A (approximately 14 L/biopile); and so on in diminishing volumes for each biopile throughout the 12-week period in order to maintain the optimum 50% moisture content target.

Table 5: Field trial schedule and water addition rates in litres per biopile.

Week	**Activity**		
0	Establish biopiles		
	Turning and watering schedulethererafter		
	Weekly	Bi-weekly	Water added (L/biopile)
1	X	—	667
2	X	X	800
3	X	—	58
4	X	X	100
5	X	—	67
6	X	X	133
6	Sample biopiles and analyse		
7	X	—	—
8	X	X	133
9	X	—	50
10	X	X	—
11	—	—	—
12	—	—	—
12	Sample biopiles and analyse		

Analyses of post-composting samples were conducted after Week 6(with a reduced suite of analytes) and again at the end of the trial after Week 12. Samples were obtained by collecting four x 250 g grab samples from points around eachbiopileat 30 cm deep and composited into one 1.0 kg sample.Samples from A-1-A, A-2-A and A-3-A were composited to create one sample of biopileA turned weekly, samples from A-1-B, A-2-B and A-3-B were composited to create one sample of biopile A turned bi-weekly, and so on to form four samples. Analyses of samples were conducted at an accredited IDAC Merieux laboratory, using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and gas chromatography-mass spectrometry (GC-MS).

The following analytesin each sample were measured: pH using 1:5 soil/water leach; EC;bulk density; moisture content; OM; OC;TN;C/N ratio; soluble calcium (Ca); soluble K; copper (Cu);iron (Fe); Mg; TP; zinc (Zn); cation exchange capacity (CEC); and pathogens salmonella, faecal coliforms, and *Escherichia coli* (*E.coli*) using the most probable number (MPN) method reported as colony forming units (cfu).Odour was rated by three, on-site operators using the aforementioned self-report rating scale.

Post-composting fugitive germination was used as measure of compost maturity and represents the number of seeds to spontaneously sprout from compost after Week 12. A count of physical impurities, such as glass, plastic, metal and stones, was also carried out after Week 12 and reported as a percentage of compost. For the purposes of brevity in this paper, only the 12-week average weekly temperatures and moisture contents for each biopile have been presented.

III. RESULTS AND DISCUSSION

Table 6 presents the interim chemical analysis after Week 6. From this data it can be concluded that pH in all biopilesis near-neutral, EC is high at an average of 18 dS/m, OM averaged 19%, OC averaged 11%, TN averaged 0.90%, C/N ratios averaged a low 12:1, heavy metals ranged from a low of 0.12 mg/kg for Cd to a high of 89 mg/kg for Zn, with low concentrations of pathogens. On most measures, no obvious differences can be observed in these data when comparing weekly and bi-weekly turning or when comparing different addition rates of MARR, although OC was much lower in bi-weekly compared to weekly turned manure and bedding sand compost, and faecal coliforms were more than double in bi-weekly compared to weekly turned biopiles. Based on measures of EC and C/N ratio, this compost product would not meet the standard set for compost in Saudi Arabia, but would in all other respects.

Table 6: Chemical properties of biopiles after Week 6 compared to the Saudi Arabia compost standard.

Parameter (Unit)	**Code**					**Saudi Arabia Standard**[†]
	A-1-A, A-2-A, A-3-A	**A-1-B, A-2-B, A-3-B**	**B-1-A, B-2-A, B-3-A**	**B-1-B, B-2-B, B-3-B**	**C-1, C-2, C-3**	
pH	7.8	7.6	7.7	8.0	7.0	5.5-8.5[‡]
EC (dS/m)	18	17.4	19.1	18.8	17.2	<4.0
Organic matter (%)	19	19.1	26.5	13.2	19.6	40
Organic carbon (%)	10.5	11.2	15.6	7.7	11.5	[§]

Total nitrogen (%)	0.89	0.91	0.84	0.82	1.0	§
C/N ratio	12:1	12:1	19:1	9:1	11:1	15-25:1§§
Cd (mg/kg)	0.24	0.28	0.12	0.21	0.36	§
Cu (mg/kg)	84.9	92.5	75.4	65.2	121	150
Ni (mg/kg)	3.8	4.1	3.5	4.1	4.2	§
Pb (mg/kg)	0.97	0.90	0.56	0.71	0.93	§
Zn (mg/kg)	64.5	65.5	89.6	84	68.5	350
Salmonella (cfu)	0	0	0	0	0	0
Faecal coliform (cfu)	88	200	40	120	480	<1,000
E.coli (cfu)	32	36	4.0	4.0	8.0	<1,000

[†] Source: Al-Turki [2] unless otherwise noted; [‡] Al-Turki maintains that a pH of 7.0-7.5 is desirable for compost in Saudi Arabia, however Alzaydi et al. [3] maintain it is 5.5-6.5; international standards are typically in the range of 5.5-8.5 [e.g., 25]; [§] No standard, according to Al-Turki [2];[§§]C/N ratio for commercial Saudi Arabia compost should be between 15:1 and 20:1 according to Alzaydi et al. [3] and 25:1 according to Al-Turki[2].

The composting process generally follows three basic phases: first, a mesophilic or “moderate temperature” phase which lasts between a few days and a week as the temperature rises above 40^{0}C; second, a thermophilic or “high temperature” phase which can last for a few days up to a few months at temperatures above 50^{0}C; and third, a “cooling or maturation” phase back to 40-45^{0}C; each phase is dominated by either mesophilic then thermophilic and then again mesophilic microorganisms, including actinomycetes and saprophytes. All the temperature curves presented in Figures 1-3 are typical of this typical three-phase process.

Average weekly temperatures of the A biopilesare presented in Figure 1, with weekly turned biopiles A-1-A, A-2-A and A-3-A to the left and bi-weekly biopiles A-1-B, A-2-B and A-3-B to the right. All biopiles registered a temperature of 42^{0}C when established. Figure 1 shows that weekly turned biopiles reached 52^{0}C within one week, A-1-A rose sharply to 65^{0}C and A-2-A rose sharply to 60^{0}C by Week 2, and then all three fluctuated between 55^{0}C and 60^{0}C until Week 6, when a sharp drop resulted inbiopiles stabilising at 45^{0} C. The average daily temperature (i.e., average of 90 days) in these biopiles was A-1-A = 50.7^{0}C, A-2-A = 50.8^{0}C and A-3-A = 53.9^{0}C. While the temperature in A-3-A with 1.5% MARR was significantly higher than both A-1-A and A-2-A, no other obvious temperature trendsattributable to MARR were detected.

Bi-weekly biopiles uniformly rose to 60^{0}C by Week 2, fluctuated between 53^{0}C and 60^{0}C during Weeks 2-6, and then dropped sharply and stabilised to 45^{0}C after Week 7. The average daily temperature in these biopiles was A-1-B = 52.9^{0}C, A-2-B = 52.9^{0}C and A-3-B = 52.8^{0}C, therefore no obvious temperature trend was detected in these biopiles. When comparing the average daily temperatures of weekly turned biopiles with bi-weekly turned biopiles (weekly turning = 51.8^{0}C compared to bi-weekly turning = 52.8^{0}C) and lower and higher MARR addition rates, no significant difference was observed.

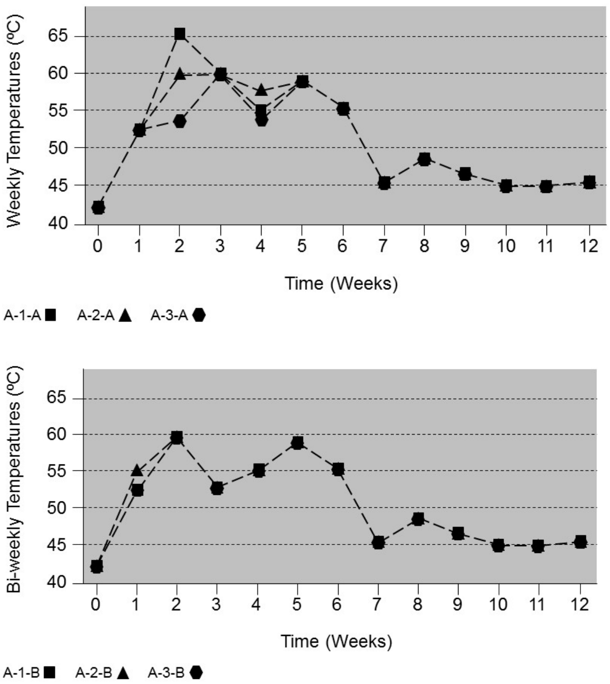

Fig.1. Average weekly temperatures in Abiopiles between Weeks 0-12.

The average weekly temperatures of B biopiles are presented in Figure 2, with weekly turned biopiles B-1-A, B-2-A and B-3-A to the left and bi-weekly biopiles B-1-B, B-2-B and B-3-B to the right. All biopiles registered a temperature of 42^{0}C when established. As was the case for Abiopiles, Figure 2 shows that all weekly turned biopiles reached >52^{0}C within one week, B-1-A rose sharply to 65^{0}C and B-2-A rose sharply to 60^{0}C by Week 2, and then all three fluctuated between 50^{0}C and 60^{0}C until Week 6, when a sharp drop resulted in all three biopiles stabilising at 45^{0}C. The average daily temperature in these biopiles was B-1-A = 51.1^{0}C, B-2-A = 52.1^{0}C and B-3-A = 51.7^{0}C, therefore no obvious temperature differences were detected between biopiles with different MARR addition rates.

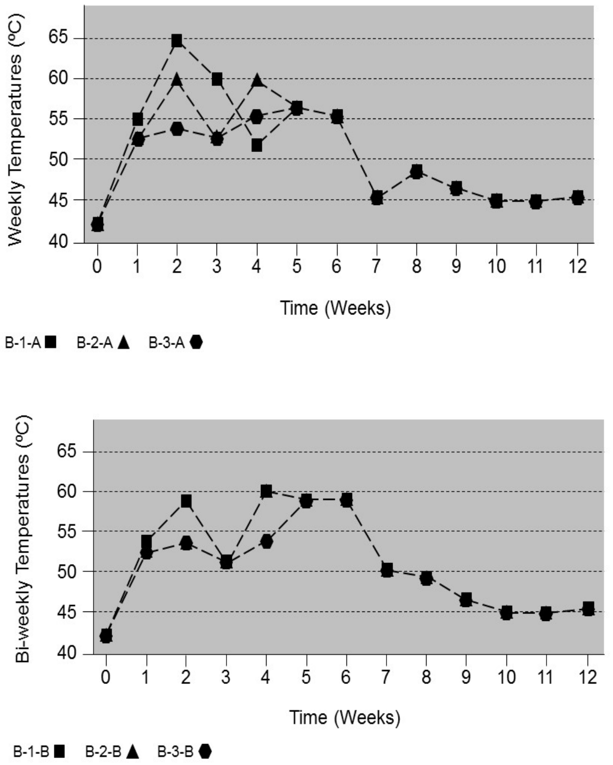

Fig.2. Average weekly temperatures in B biopiles between Weeks 0-12.

Bi-weekly biopiles uniformly rose to 55-60^{0}C by Week 2, fluctuated between 53^{0}C and 60^{0}C between Weeks 2 and 6, and then dropped sharply and stabilised to 45^{0}C after Week 7. No significant difference was observed between weekly and bi-weekly turned biopiles or between lower and higher MARR addition rate biopiles. The average daily temperature in these biopiles was B-1-B = 59.4^{0}C, B-2-B = 59.1^{0}C and B-3-B = 58.9^{0}C, and therefore no obvious temperature difference was detected between biopiles with different MARR addition rates. When comparing the average daily temperatures of weekly turned biopiles with bi-weekly turned biopiles (weekly turning = 51.6^{0}C compared to bi-weekly turning = 59.1^{0}C), a significant difference of 7.5^{0}C (or 13%) was observed.

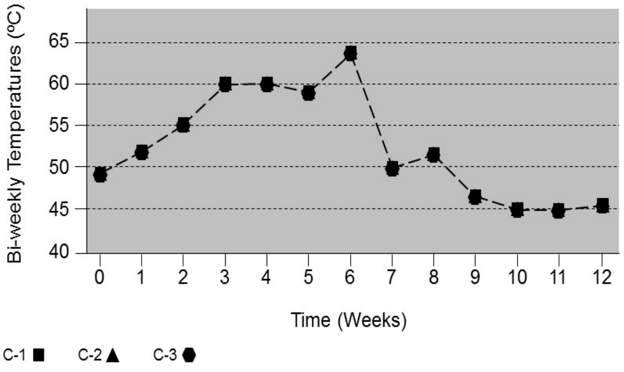

Fig.3. Average weekly temperatures inC biopiles between Weeks 0-12.

The average temperatures of bi-weekly turned biopiles C-1, C-2 and C-3 are presented in Figure 3. All three biopiles displayed the same temperature evolution, starting at 48ºC, rising steadily to 64ºC by Week 6, dropping sharply to 50ºC in Week 7, before steadily declining to a stable 45ºC between Weeks 9-12. Unlike biopiles A and B, biopiles C rose steadily between Weeks 0 and 6, and reached their highest temperatures in Week 6 rather than in Weeks 2-5.Average daily temperatures were 50.1^{0}C for C-1 and 49.6^{0}C for C-2 and C-3, therefore no obvious temperature differences were detected between biopiles with different MARR addition rates. Temperature curves and final temperatures of biopiles A, B and C are consistent with those observed for cow manure by Augustin and Rahman [24].

The ability of heat to eliminate pathogens and kill weed seeds during the composting process, thereby producing products which do not pose a risk of spreading disease or weeds, is considered advantageous. Consequently, regulatory standards stipulate process and product-related requirements to ensure "pasteurisation". To achieve pasteurisation, international process standards recommend composting at 55^{0}C for a minimum of three consecutive days with an average temperature of >45^{0}C over 14 days to achieve zero salmonella per 50g of compost, <1,000 cfu/25g for faecal coliforms, and <100 cfu/25g for *E.coli*[e.g., 26]. According to Al-Turki, Saudi Arabia has set the following standards for pathogens in compost products: salmonella = 0 cfu; faecal coliforms = <1,000 cfu; and *E.coli* = <1,000 cfu [2]. As shown in Table 6 and Figures 1-3, these process and compost quality requirements were met by Week 6 in this trial, thus suggesting the compost in this trial reached stability by Week 6.

The average volumetric weekly moisture contents of biopiles A-1-A, A-2-A, A-3-A, B-1-A, B-2-A and B-3-A between Weeks 0-12 are presented in Figure 4 (left); these data are representative of the moisture content ranges and trends in biopilesA-1-B, A-2-B, A-3-B, B-1-B, B-2-B and B-3-B. These data indicate that moisture contents for biopilesA and B was 40% at establishment, decreased to between 30-40% during the first three weeks and then rose steadily to about 50% by Week 7, after which it decreased sharply and stabilised at 35%. Figure 4 also presents the moisture contents for biopiles C-1, C-2 and C-3 (right), which indicate that moisture contents were more stable in these biopiles, with contents between 32% and 38% at establishment, rising steadily by Week 4 when they reached 40-45%, and then declined and stabilised at 35-40% before settling to 30%.

The moisture target range of 40-60% for biopiles was achieved about half the time and followed the three-phase rises and falls in temperature described above, but may have resulted in a depletion in mesophilic and thermophilic microbial counts when below 40%. Moisture content averaged 34% at the end of the trial and was within the acceptable range of 20-40%, although Al-Turki found that comparable compost in Saudi Arabia only had a moisture content of 4% but nine other compost samples in Saudi Arabia had an average 25% moisture content [2].

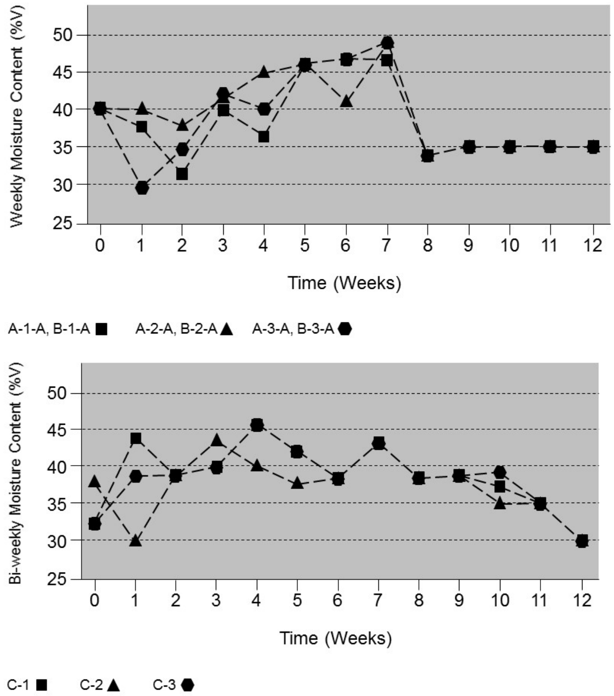

Fig.4. Average weekly moisture contents of biopiles A-1-A, A-2-A, A-3-A, B-1-A, B-2-A and B-3-A(left) and C-1, C-2 and C-3 (right) between Weeks 0-12.

Table 7 presents the chemical analysis conducted after Week 12; based on this data, it is reasonable to conclude that no discernible differences occurred between biopiles with different MARR addition rates. From this data it can also be concluded that pH has been slightly elevated, although in only manure and bedding sand compost would this make it unsuitable for reuse in Saudi Arabia and is comparable to other cow manure compost in the Kingdom. EC was high at an average of 10.8 dS/m, placing it above the standard but again was comparable to the EC of other cow manure compost in the Kingdom, and was lower than the starting average of 14.7 dS/m. It can be concluded that the salinity of bore water used as the moisture source in this trial may have contributed to elevated pH and EC, a conclusion borne out by geochemical research conducted on ground and spring water in the area [27]. While MARR also has an above-neutral pH and elevated EC concentrations, addition rates of 0.5-1.5% would likely not have contributed to these data. Average bulk density observed by Alzaydi et al. in nine commercial Saudi compost samples was 0.52 kg/L [3], which was comparable to the average 0.74 kg/L observed here. While a bulk density of 0.82 kg/L could be described as "high" in biopiles B (the bulk density of pure manure is 0.4 kg/L), this density was likely due to the presence of bedding sand, which has a bulk density of about 1.2 kg/L.

Table 7: Chemical and physical properties of biopiles after Week 12 compared to another cow manure compost and the Saudi Arabia compost standard.

Parameter (Unit)	Code					Cow Manure Compost[†]	Saudi Arabia Standard[†]
	A-1-A A-2-A A-3-A	A-1-B A-2-B A-3-B	B-1-A B-2-A B-3-A	B-1-B B-2-B B-3-B	C-1 C-2 C-3		
pH	8.5	8.3	8.9	8.9	8.1	8.8	5.5-8.5[††]
EC (dS/m)	10.5	10.8	11.8	11.1	10.2	8.0	<4.0
Bulk density (kg/L)	0.72	0.70	0.77	0.88	0.64	—	0.52[‡]
Moisture content (%)	35	34	35	34	30	4.0	20-40[‡‡]
OM (%)	11.7	15	19	16.5	15.4	27	40
OC (%)	6.9	8.8	11.1	9.7	9.1	15.7	[§]
TN (%)	0.52	0.55	0.68	0.62	0.72	1.1	[§]
C/N ratio	13:1	16:1	16:1	15:1	13:1	13:1	15-25:1[§§]
TP (mg/kg)	0.22	0.34	0.41	0.41	0.28	—	[§]
N/P ratio	1:0.6	1:0.4	1:0.4	1:0.4	1:0.4	—	—
Soluble Ca (%)	0.36	0.36	0.34	0.36	0.38	—	[§]
Soluble K(%)	0.89	0.92	1.2	1.1	0.80	—	[§]
Cu (mg/kg)	84.9	92.5	75.4	65.2	121	8.3	150
Fe (mg/kg)	791	756	858	789	815	—	[§]
Mg (mg/kg)	0.30	0.30	0.36	0.33	0.28	—	[§]
Zn (mg/kg)	64.5	65.5	89	84	68.5	96	350
CEC (meq/100g)	18.3	19.5	17.5	13	18.2	—	[§]
Salmonella (cfu/25g)	0	0	0	0	0	0	0
Faecal coliform (cfu/25g)	0	0	0	0	0	1,600	<1,000
E.coli (cfu/25g)	0	0	0	0	0	—	<1,000
Odour (1-5)	1	1	1	1	1	—	[§]
Fugitive germination	0	0	0	0	0	80%[#]	[§]
Physical impurities (%)	0.10	0.60	0.0	0.16	0.14	—	[§]

[†]Source: Al-Turki [2] unless otherwise noted; "Cow Manure Compost" data were derived from Al-Turki[2] from data generated in Saudi Arabia; [††]Al-Turkimaintains that a pH of 7.0-7.5 is desirable for compost in Saudi Arabia [2], however Alzaydi et al. maintain it is 5.5-6.5 [3]; international standards are typically in the range of 5.5-8.5 (e.g., 25, p. 57); [‡] Average bulk density observed by Alzaydi et al. in nine commercial Saudi compost samples [3]; the type of compost (i.e., cow manure or other source) is not referenced by Alzaydi et al., although 40% were derived from a combination of "animal and vegetative" sources [3]; [‡‡]Alzaydi et al. found an average moisture content of 25% in nine Saudi compost samples [3]; [§]No standard, according to Al-Turki [2]; Alzaydi et al. reported average OC in eight commercial Saudi compost samples was 19% [3]; [§§]C/N ratio for commercial Saudi Arabia compost should be between 15:1 and 20:1 according to Alzaydi et al. [3] and 25:1 according Al-Turki [2], however Alzaydi et al. found a range of 7:1 to 73:1 in nine Saudi compost samples [3]; [#] Al-Turkiused the Germination Index (GI) to measure phytotoxicity and seed germination of compost in Saudi Arabia [2]; a greater than 80% GI means compost is mature and phyto-toxin free (meaning after a prescribed time 80% of seeds planted in compost germinated). Due to the low concentration of heavy metals and absence of seed germination, the compost in this study could reasonably be estimated to have a GI >80% and was "mature", however pH and EC may have adversely affected GI. Al-Turki's GI is different to "fugitive germination", which measures the number of fugitive seeds to spontaneously sprout in compost after ten days.

As expected due to microbial digestion, over the trial period OM decreased from 27% to an average of 19% after Week 6 and to 13.3% after Week 12 in compost A, was largely unchanged from 18.7% to an average of 19% after Week 6 and 17.7% after Week 12 in compost B, and decreased from 34.5% to 19.6% after Week 6 and 15.4% after Week 12 in compost C.All OM percentages were lower than the standard 40%, but closer to the 27% observed elsewhere in Saudi Arabia[2]. Similarly, OC decreased from 15.9% to an average of 10.8% after Week 6 and to 7.8% after Week 12 in compost A, was largely unchanged from 11% to an average of 11.6% after Week 6 and 10.4% after Week 12 in compost B, and decreased from 20.3% to 11.5% after Week 6 and 9.4% after Week 12 in compost C.The average of OC in all biopiles was about half the observed percentage in comparable cow manure compost[2].

TN was 0.9% at establishment and remained unchanged after Week 6, but decreased to 0.53% after Week 12 (a 42% decrease) in compost A; TN decreased from 1.1% to an average of 0.83% after Week 6 and 0.72% after Week 12 (a 35% decrease) in compost B, and decreased from 1.4% to 1.0% after Week 6 and 0.72% after Week 12 (a 49% decrease) in compost C. According to Raviv et al., average TN losses during a typical composting process are generally about 40% [28], which was observed in this trial, but can be as high as 70%[23, 29].

C/N ratio was generally stable throughout the trial, decreasing slightly from 14:1 at establishment to an average of 12:1 after Week 6 but increasing to 15:1 after Week 12 in compost A.C/N ratio was 12:1 at establishment increasing to an average of 14:1 after Week 6 and again to 15:1 after Week 12 in compost B, and was 15:1 at establishment decreasing to 11:1 after Week 6 but increasing to 13:1 after Week 12 in compost C.Except for weekly turned A-1 and bi-weekly turned C biopiles which were slightly under the recommended C/N ratio after Week 12, all composted material met the recommended standard for C/N ratio in Saudi Arabia, but no significant difference was found between the weekly and bi-weekly turned biopiles for OM, OC, TN or C/N ratio.

Heavy metal concentrations in produced compost were below the requirement standard for Cu and Zn, although Cu concentrations were significantly higher than other cow manure in Saudi Arabia. Cation exchange capacity (CEC) is relevant to this study because it relates to soil fertility; CEC measures the total number of cations available for exchange with water as a result of negatively charged particles in the compost holding positively charged cations by electrical attraction. Sand typically has a CEC of about 1.0-5.0meq/100g, silty loams have a CEC of about 5.0-15 meq/100g, and clay loams have a CEC of >15 meq/100g, which is how the composts produced in this trial would be classified.After Week 12, all 15 biopiles recorded zero salmonella, faecal coliforms and *E.coli*, which was at or below the Saudi Arabia standard for compost, and odour in all biopiles was rated "1" by independent raters, meaning any odouremanating from biopileswas not offensive or unpleasant and was tolerable to all.Zero fugitive seeds germinated in all biopiles within ten days of completion of the trial, and low concentrations of physical impurities were detected.

Given the previous research on TP and P-retention cited above, of relevance also are the findings related to phosphorus. Pre-trial concentrations of TP in the four main feedstocks were 0.32% for pure manure, 0.31% for manure and bedding sand, 0.19% for primary settling basin sludge, and 0.18% for leftover feed. After the three biopiles were formed, these were reduced to 0.25% for A and 0.18% for B, and increased to 0.23% for C. After Week 12, TP average 0.28% for A, 0.41% for B, and 0.28% for C. While the trial design did not allow for discrimination between biopilesA-1-A and A-2-A or between biopiles A-2-A and A-3-A (i.e., to determine if P-retention was higher in biopiles amended with higher addition rates of ARR), the results do suggest that P was generally concentrated over the 12-week trial, which is consistent with other findings on cow manurecomposting [30].

Lambert et al. note that cow manure has a nitrogen-to-phosphorus(N/P) ratio of about 1:0.2, but shifts to 1:0.3 as a result of composting as a result of reducing N and concentrating P [31]. In this study, the N/P of pure cow manure was 1:0.3 (Table 1) and about 1:0.4 in biopiles prior to composting (Table 3). Augustin and Rahman suggest that manure compost (derived from a variety of animals) typically has a (N/P) ratio of 1:2 [24], however, in this study N/P ratios averaged 1:0.5 for biopile A; 1:0.4 for biopile B, and 1:0.4, meaning N/P ratios and trendswereconsistent for cow manure composting, as cited by Lambert et al. [31] and Pettygrove et al. [32].Excluding the higher EC data and lower OM percentages, compost in all biopiles would conform to acceptable standards in Saudi Arabia, and therefore the research question of this study was partially answered in the affirmative.

IV. CONCLUSION

Several research design flaws can be identified, some of which occurred because of lack of resources. The first weakness in the design of this study was the way samples were collected, composited and analysed. This design flaw meant that it was impossible to isolate the role, if any, MARR had on composting (excluding daily temperature and moisture content data, which did not get composited) because post-compost chemical and physical properties data from biopile A-1-A (0.5% MARR), for example, was not isolated from data derived from biopile A-2-A (1.0% MARR) or from biopile A-3-A (1.5% MARR) but were composited to form “weekly turned”biopile A data. Therefore, the data required for distinguishing between weekly and bi-weekly turning was identified, but data required for distinguishing between addition rates of MARR were not. Due to this error in design, the true role of MARR cannot be fully identified, although it is not unreasonable to conclude it was negligible.

However, it is also possible that not enough MARR was added to any biopile to make a decisive difference to temperature, moisture content or chemical and physical parameters of dairy farm compost. Given that previous research on composting and ARR utilised addition rates of between 1-5%, it is reasonable to assume that 0.5-1.5% addition rates of MARR may have been too low to register differences (due to financial and logistical constraints in this trial, no more than the 4.5 tonnes of MARR could be shipped to Saudi Arabia from Australia, thus necessitating the low addition rates). An alternate design might have considered using fewer feedstocks and therefore fewer biopiles with higher addition rates of MARR to overcome this shortcoming, but the research was also dictated to by the needs of the site-owner who wished to investigate the possibility of composting using as many different feedstocks generated at the dairy farm as possible.

A third design flaw relates to the use of a front-end loader for biopile turning. It is generally considered necessary in composting to use a windrow turner or bucket tractor [24], neither of which were available in Saudi Arabia during the field trial. This limitation meant that biopiles may not have been thoroughly mixed and aerated on turning.A final design flaw relates to the use of volumetric versus gravimetric water addition rates and moisture content reporting.

For these reasons, further research on composting in Saudi Arabia is needed, and more sophisticated research designs and equipment should be employed. If MARR has a role to play in composting, higher addition rates than the 1.5% used here must be employed, however the economic viability of such higher rates, particularly when shipping product to sites at great distance from the source of MARR, may make that conclusion unrealistic. Nevertheless, the results of this trial suggest that weekly, and specifically bi-weekly, turning of compost using cow manure and other carbonaceous waste streams at a dairy farm in Saudi Arabia result if a viable composted product.

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