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Drying dairy manure using a passive solar still: A case study

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A R T I C L E I N F O

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A B S T R A C T

The pyrolysis of wet biomass such as faecal sludge and cow manure requires an extra drying step to reduce the moisture content before pyrolysis can occur. Open-air solar drying is a technique routinely used to dry faecal sludge and dairy manure. In this method water held within the biomass is lost to the atmosphere. A simple solar still was constructed in order to both dry cow manure and to capture water as part of the drying process. Measurements included solar radiation, cover temperature and internal solar still temperature and chemical analysis of the distillate. The maximum internal temperature of the solar still was recorded at 52.9 °C and the minimum recorded at 10.1 °C. The key objectives were to investigate the use of solar still technology in drying cow manure and determine the chemical properties of the distillate with a view to its re-use as irrigation water. The moisture content of the cow manure was reduced by 13%, however, the pathogen content of the resultant distillate contained 8,010 *Escherichia Coli* per 100 ml.

1. Introduction

The re-use of water is becoming increasingly important due to a significant rise in worldwide water requirements caused by a dramatic increase in population and economic growth [1]. Many locations worldwide suffer from water scarcity, sharp increases in urban populations and increasing requirements for irrigation water. An ever-increasing requirement for water despite a constant or diminishing supply and droughts caused by climatic conditions result in many locations experiencing water stress. The untreated disposal of wastewater and run off from farms also contribute to water stress by polluting freshwater bodies and reducing the available amount of safe, clean water [2]. Most people affected by water scarcity live in developing countries with climate change likely to exacerbate the problem. A report by United Nations indicates that nearly 6 billion peoples will suffer from clean water scarcity by 2050 [3]. Agriculture is just one of many industries along with food processing, textile manufacturing; and automotive industries that require vast quantities of water [4]. Agriculture accounts for about 70% of global water withdrawals [3]. Dairy farms in particular use vast quantities of water. One estimation is that approximately 435 L of water is used per cow per day which does not even consider the water needed for milking, cleaning, or irrigating the crops consumed by the livestock [5]. There is potential to address global water scarcity by capturing water from the drying of dairy manure for use as irrigation water in agriculture. The bacteria content of water captured via this method is a significant issue, however guidelines exist that outline a risk-managed based approach for the safe use of wastewater in agriculture [6]. The guidelines consider the level of wastewater treatment (primary, secondary etc.) and the health protection controls such as irrigation method, crop restriction, and application and control of human exposure. Therefore, lower levels of wastewater treatment may be deemed enough if implemented in conjunction with other risk reduction methods such as withholding periods, produce washing, disinfection and cooking.

Open-air thin-layer solar drying and thermal drying using solar dyers are two common methods to dry animal manure [7,8] and foodstuffs [9–11]. In solar drying, air is ventilated through small holes at the top of the dryer. The air inside the dyer gets warm and removes the moisture from the fruits, vegetables, and the crops in the dryer. With this method and the open-air solar drying method, moisture from the drying process is lost to the atmosphere, however, recapturing moisture could be achieved with the use of a solar still. Solar stills have historically been utilized to desalinate saltwater or brackish water [12–14] although this technology has been utilized with other materials such as milk [15], sewage sludge [16], sewage water, reverse osmosis (RO) reject water [17], landfill leachate [18], sanitary wastewater, palm oil mill effluent [19] olive mill wastewater [20,21] and textile industry effluent [22].

Passive solar stills are completely airtight structures with a dark-coloured basin containing salt water, an angled transparent cover, and a form of guttering to collect the water which flows out of the still through an outlet pipe. Incident solar radiation passes through the transparent cover which is absorbed by the dark-coloured basin heating up the saltwater. The water evaporates and rises until it hits the cooler inner surface of the transparent cover. The water droplets are then collected in a gutter and flow out through the outlet pipe to be collected. Most of

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Table 1
Review on various researcher's work on different feeds used in solar stills.

Refs.	Material	Passive/active	Modifications
[12]	Saline water	Passive	Floating plates
[13]	Saline water	Passive	Blue stones and cow dung cakes
[14]	Saline water	Active - evacuated tubes supply extra heat	Double basin design with heat dissipation fins
[15] Review	Milk	Active	–
[16]	Wastewater sludge	Passive	–
[19]	Palm oil mill effluent Sanitary wastewater	Passive	Stepped
[22]	Textile industry effluent	Passive	Simple still and stepped
[18]	Landfill leachate	Active – solar air preheater	Heat dissipation fins
[21]	Olive mill wastewater	Active - underfloor heating	–
[20]	Olive mill wastewater	Passive	Simple solar still
[17]	Sewage water (RO) reject water	Passive	Simple solar still

these designs also feature an inlet pipe allowing saltwater to be pumped into the still. There are many different designs of solar stills which have been reviewed extensively already [23–27], including simple solar still plate designs [28], solar stills that utilize nanofluids and nanoparticles to increase heat transfer [29–31] and the use of energy storage materials to increase distillate yield [32,33].

Once animal manure is sufficiently dewatered in a solar still it can be further processed to produce biochar which has gained increasing attention in recent years. Biochar is produced via pyrolysis where biomass such as dried dairy manure is heated to temperatures greater than 250 °C in the absence of oxygen [34]. The main challenge that is currently limiting the large-scale production of animal waste biochar is the extra step needed to reduce the moisture content.

Biochar itself has multiple uses including as media in biofilters to remove faecal indicator bacteria (FIB) from stormwater [35,36]. A biofilter is typically a layer of organic material, such as compost and wood chips that support a microbial population. Studies have shown that biofilters incorporating biochar have a higher *E. coli* removal rate than with sand on its own [37,38]. This is due to the increase in attractive forces i.e. hydrophobic and steric interactions [39] and the attachment of bacteria via straining due to the rough surface and uneven surface of biochar [37,40]. Therefore, biochar produced from dried dairy manure could be utilized as part of a biofilter to remove bacteria from the distillate from drying dairy manure in a solar still.

This case study investigates the drying of cow manure in a simple passive solar still. The specific objectives of this study were to determine the temperatures reached inside the still, the chemical composition of the resultant distillate and the moisture reduction of the dairy manure. A biofilter was also constructed using sand and biochar as media to aid in removing any pathogenic bacteria from the distillate.

Dairy manure was placed in a simple solar still constructed from wood and polycarbonate for a period of 2 weeks. Solar radiation, cover temperature, inside temperature and humidity were measured for the duration of the experiment. The distillate before and after passing through the biofilter was analysed for E. coli, total coliform numbers, pH and turbidity.

Table 2
Proximate analysis, elemental analysis, pH, EC and surface area measurements of faecal sludge biochar used in this study (EC = Electrical Conductivity, C= Carbon, N= Nitrogen, S= Sulphur, Oxygen, SBET = Surface area measured by BET, TPV = Total pore volume, SSA = Specific Surface area, CEC=Cation Exchange Capacity).

Parameter	Unit	Biochar
pH	[]	11.82 ± 0.01
EC	[$mS.cm^{-1}$]	1.79 ± 0.17
Moisture	[%]	2.15 ± 0.31
Ash	[%]	67.0 ± 2.68
C	[%]	23.79
N	[%]	1.13
H	[%]	0.73
S	[%]	0.27
O	[%]	7.08
H/C	[]	0.4
C/N	[]	24.6
O/C	[]	0.2
$S_{BET}N_2$	[$m^2.g^{-1}$]	3.69 ± 0.36
N_2 TPV	[$cm^3.g^{-1}$]	0.011
S_{BET} CO_2	[$m^2.g^{-1}$]	74.20 ± 4.0
CO_2 μSSA	[$m^2.g^{-1}$]	99.62 ± 4.5
CO_2 μPV	[$cm^3.g^{-1}$]	0.027
CEC	[$cmol.kg^{-1}$]	41.9 ± 2.2

2. Materials and methods

2.1. Geographical location

The solar still was tested in a field in Swansea, Wales (51° 42′ 18″ N 3° 54′ 36.72″ W) for approximately 2 weeks during July/August 2020. The average UK annual solar resource is 101.2 Wm^{-2}, (0.1 kWm^{-2}) ranging from 128.4 Wm^{-2} in the south of England to 71.8 Wm^{-2} in the northwest of Scotland.

2.2. Solar still

The schematic of the solar still used for this study is depicted in Fig. 1. This simple solar still design is similar to the ones employed for seawater desalination. The solar still was designed from locally available materials in line with previous work [23] that emphasised the need for solar stills to be built by locally existing materials using simple technology so that the stills can be deployed everywhere with minimal maintenance required. The basic shape of the still was constructed from chip board wood and sealed with a water-proof sealant. The bottom and internal sides were painted black to order to enhance the absorptance of the incident solar radiation. The transparent cover used was a greenhouse panel made of polycarbonate (0.003 m thickness).

A door was installed at the back of the still to access the cow manure in order to agitate it and prevent crust formation. This crust formation at the surface has also been observed in faecal sludge drying. Crust formation can form a barrier for drying of the core of the faecal material, by restricting moisture mass transfer [41]. After 4 days of the still being operational polyisocyanurate foil backed sheets (2.54 cm thickness) were added to the inside of the still to reduce thermal losses. The wooden door consisted of a large piece of chipboard attached at the bottom using hinges and 3 locks to hold the door in place. Self-adhesive foam seals were attached to the inside of the door an extra barrier to prevent moisture escaping.

The apparatus was placed outdoors, facing west, for a period of 2 weeks.

Fresh cow manure was collected from Cathelyd Ysaf Farm in the South Wales valley, approximately half a mile from the location of the solar still. Cow manure (10.0 kg) was placed in stainless steel trays (Fig. 3) to a depth of 4–6 cm. The stainless-steel trays were placed into

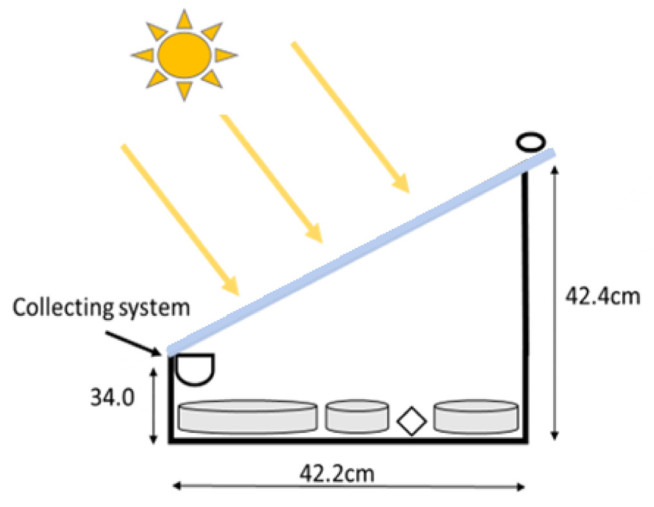

Fig. 1. Schematic of solar still- ○ indicates the position of the lux and temperature metre and ◊ indicates the position of the temperature and humidity logger.

the basin of the solar still through the built-in door (Fig 2.) The door was closed tight and the solar still was placed outdoors for a total period of 15 days. With the onset of solar radiation and the increase of temperatures the evaporation and subsequent condensation started, and it continued throughout the day. Solar radiation and cover temperature were measured every 10 min using a HOBO MX 1101 lux and temperature data logger. The temperature and humidity inside the still were measured every 30 min with an Elitech multi-use temperature and humidity data logger RC-51H model.

2.3. Biofilter

A very simple biofilter was constructed using a 250 ml plastic measuring cylinder with the lower end removed. Two pieces of bio filter sponge: one of 30 PPI (pores per inch) and one of 40 PPI were placed both at the top and at the bottom of the measuring cylinder. A layer of sand (50 g) was placed at the bottom followed by a layer of biochar (25 g) in the middle and a second layer of sand at the top (50 g). Prior to all experiments, the packed column was conditioned with 250 ml of deionized water. Downward gravitational flow was used rather than pumping the distillate upwards through the biofilter as this method is more economical. The geomedia used in this study were not sterilized prior to column experiments, neither were they rinsed in deionised water or acid washed. The sand component consisted of ultra-fine white quartz (0.1–0.7 mm). Faecal sludge biochar was supplied by Tide Technocrats and has been characterized fully in a previous study [42].

2.4. Distillate analysis

Bacterial analysis was conducted by Oakwater Laboratories based in Exeter, Devon. *E. coli* measurements were conducted using an IDEXX Quanti-tray 2000 system, a semiautomated quantification method based on the Most Probable Number (MPN) model. Total coliform measurements were conducted using the IDEXX Colilert-18/Quanti-Tray method, a worldwide ISO standard for detecting total coliforms in water (ISO 9308-2:2012). Electrical conductivity (EC) was measured using a calibrated Whatman CDM 400 EC metre and pH measurements were taken using a Voltcraft soil pH metre calibrated using pH 7 and pH 10 buffers. The analyses of pH and EC were performed in triplicate.

Chemical analysis of distillate and filtered samples were carried out by Forest Research (FR), the research agency of the Forestry Commission. All chemical measurements were conducted on duplicate samples. Total nitrogen (TN) was measured by injecting the sample into a high temperature (650–700 ºC) combustion reactor with an oxidative catalyst, converting all forms of nitrogen to nitric oxide (NO). The NO was quantitated with a chemiluminescent detector from Analytical Sciences Ltd, Thermalox model.

Ammonia was measured using the Blue book method: ISO 7150/2 – 1986 Determination of Ammonia – Automated spectrophotometric method using a Chemlab analytical model and colorimeter.

Anions were measured by filtration through a 0.45µm membrane and then analysed by Ion Chromatography (Dionex).

3. Results and discussion

3.1. Solar still parameters

Solar intensity measured in lux and cover temperature (°C) were measured for the duration of the experiment. In the solar distillation of saline water the intensity of the solar radiation (kW/m^2) and number of sunshine hours are critical factors [43]. The UK has a low global horizontal irradiance (GHI) of 2.592 kWh/m^2 relative to other countries such as Jordan which has a GHI of 6.018 kWh/m^2 [44]. This study was conducted in Swansea, Wales which experiences only 66 days of sunshine per year whereas Jordan has an average sunshine duration of more than 300 days per year [45]. This study was conducted in the summer months of July and August in the UK in order to facilitate the optimum performance of the solar still.

The maximum solar intensity was recorded at 99,942 lux at 3:52PM on day 11 of the experiment (Fig. 4). To convert illuminance (lux) to solar irradiance the equation: 1 W/m^2 = 122 ± 1 lx for outdoor natural sunlight was used [46] to provide a maximum solar irradiance 0.819 kWm^{-2}. For comparison, previous research on passive solar stills have showed maximum solar intensities of 0.979 kWm^{-2} [47] recorded in Egypt, 1.030 kWm^{-2} recorded in Saudi Arabia [48] and 1.198 kWm^{-2} recorded in India [49].

The mean solar intensity over the duration of the experiment was recorded at 24,905 lux and the maximum daily solar intensity was recorded at 50,048 lux on Day 3 of the experiment (Fig. 5).

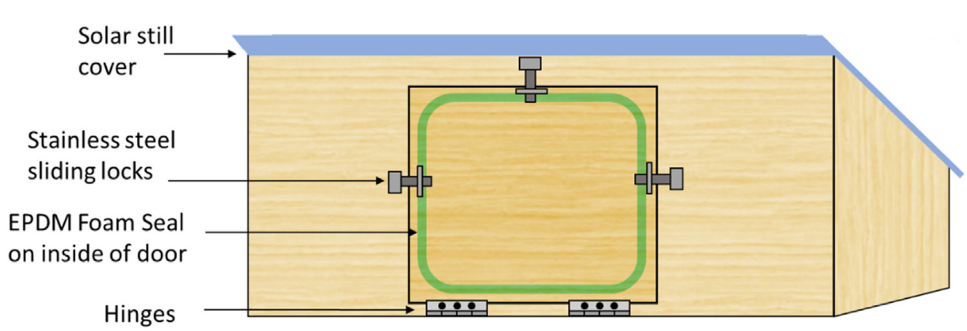

Fig. 2. Hinged door design on the back of the solar still (EPDM= Ethylene Propylene Diene Monomer, heat and weather resistant rubber).

Fig. 3. Top left - cow manure in stainless stell trays inside the solar still, bottom left - operational solar still in location, right - construction of still showing collection tube.

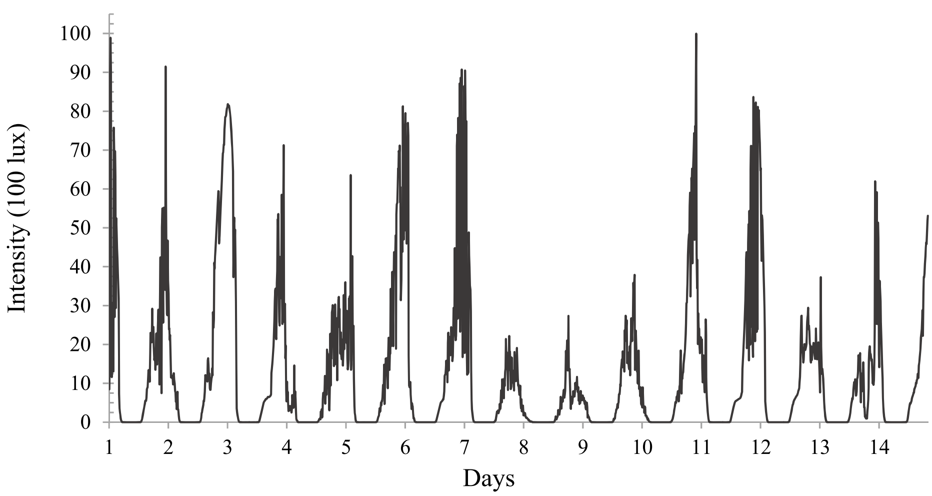

Fig. 4. Solar intensity (Lux) measured on the roof of the solar still with a HOBO MX 1101 lux and temperature data logger.

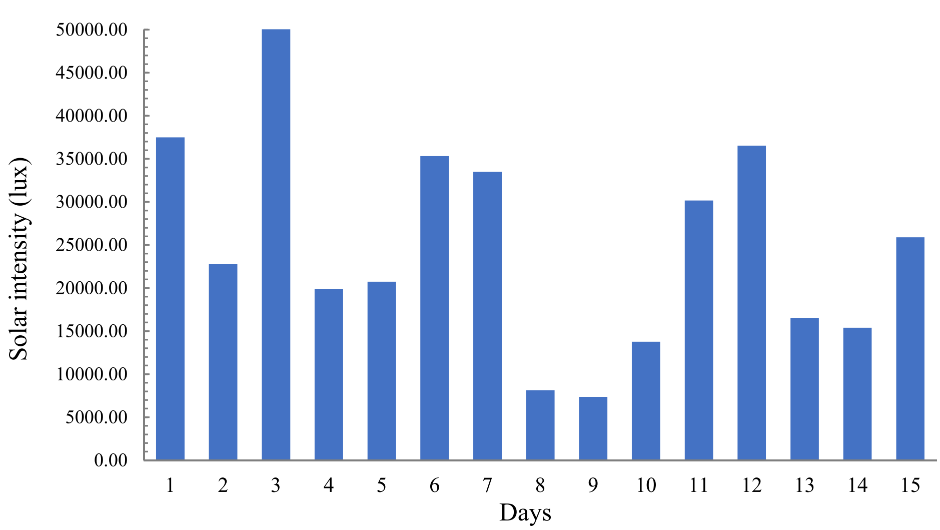

Fig. 5. Mean daily solar intensity (lux).

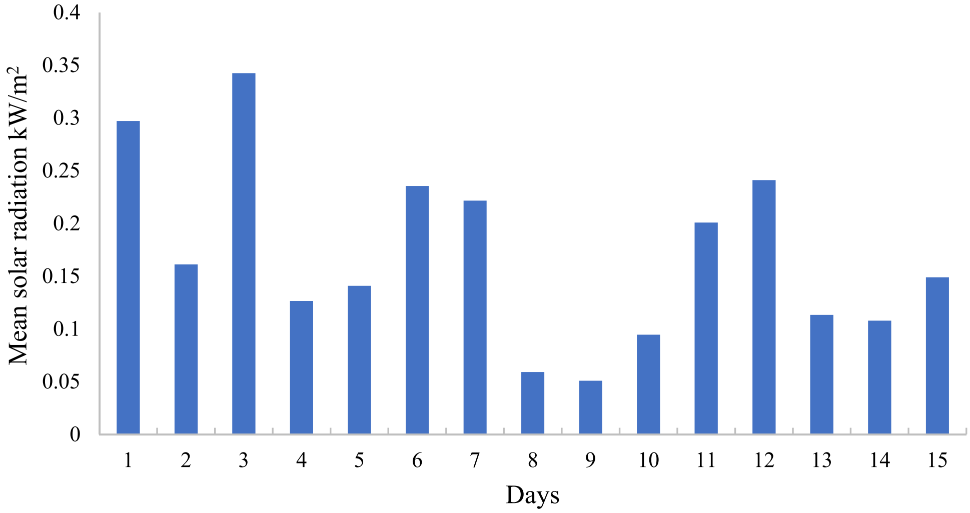

Fig. 6. Mean daily solar radiation (kW/m^2) for the two weeks of the experiment.

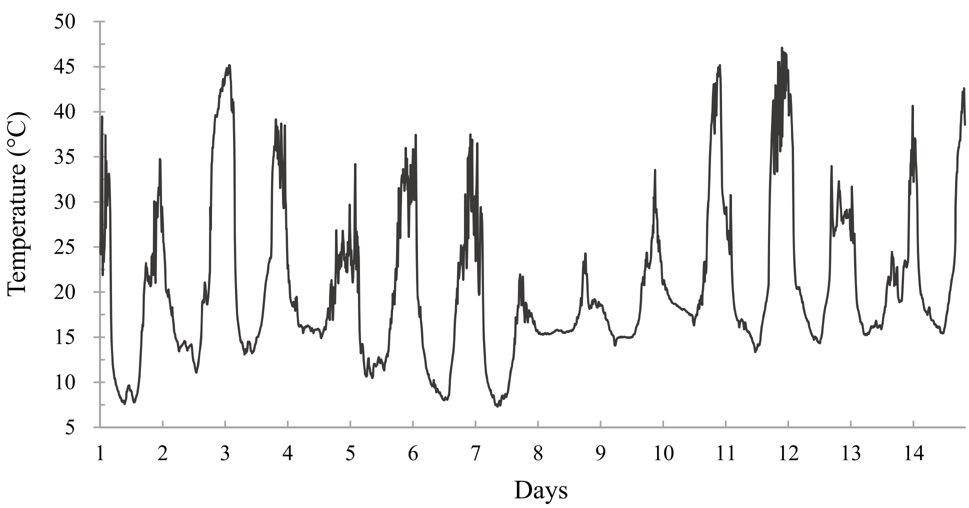

Fig. 7. Temperature measured on the roof of the solar still with a HOBO MX 1101 lux and temperature data logger.

The highest mean daily solar radiation was recorded at 0.34 kWm^{-2} on Day 3. The mean daily solar irradiance is shown in Fig. 6.

The minimum temperature of the solar still cover was recorded at 7.3 °C at night on Day 7 at 01:52AM and the maximum temperature was recorded at 47.1 °C on Day 12 at 3:42PM (Fig. 7). Maximum temperatures of solar still glass covers have been reported at 59 °C [50] and 40 °C [51].

The highest mean day-time temperature of 36.39 °C was recorded for Day 3 with the lowest day-time temperature recorded on Day 8 at 17.1 °C. Night-time mean temperatures ranged from 9.6 °C recorded on day 7 to 18.1 °C on Day 10. recorded for Day 7 (Fig. 8).

The maximum internal still temperature was recorded at 52.9 °C on day 3 at 4:17PM with a corresponding humidity of 57% (Fig. 9). Internal still temperatures have been previously reported at 42 °C and 53 °C [48], 35 °C [50] and 47 °C [49]. The maximum humidity recorded was 99% on Day 10 at 4:13PM with a corresponding temperature of 23.8 °C and minimum humidity recorded was 74% recorded on day 2.

During the night the temperatures inside the still decreased with the minimum temperature recorded at 10.1 °C on day 6. The loss of heat during the cold nights is an issue, with heat being lost from the sides and base however this can be remedied with a still constructed of thicker insulating materials. Research has shown that insulation thickness can significantly improve solar still productivity up to 80% [52] and blackened base liner and bottom and side thermocol insulation can improve still efficiency by 6% [53].

Polyisocyanurate panels were installed weekend of 1/2nd August, during this time a decrease in humidity is noted due to opening the door of the still for long periods of time. An increase in humidity was seen after installing the insulation panels. Before the polyisocyanurate panels were installed the mean humidity measured 86.4%, following panel installation the mean humidity was recorded at 89.6%. It is also worth noting that the mean solar intensity measured 14,344 lux before the panels were installed and after panel installation mean solar intensity decreased to 10,228 lux.

3.2. *Manure drying*

The total of volume of water collected after two weeks was 1.3 litres. This indicates the reduction of moisture content of the dairy manure (10.0 kg) is approximately 13%. The depth of cow manure in the solar still ranged from 4 to 6 cm. The depth of sludge is an important variable in solar drying. Depths of 25 cm have been used for drying wastewater sludge [54], and 10 mm in the case of faecal sludge [55]. For saline water it was found that output from a solar still increased when water depth was reduced from 3.5 cm to 2 cm [56]. Thus, the thickness of dairy

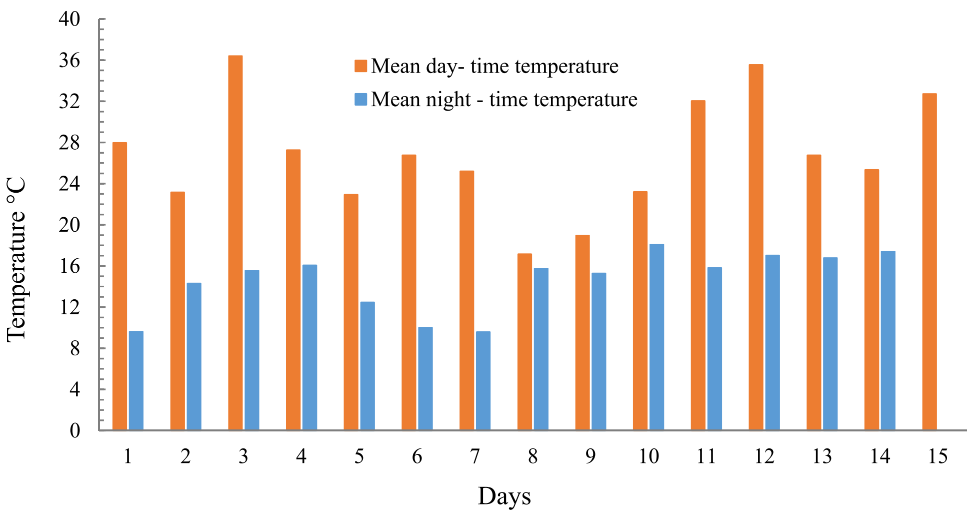

Fig. 8. Mean night-time and day-time temperatures (°C) recorded on the roof of the solar still with a HOBO MX 1101 lux and temperature data logger.

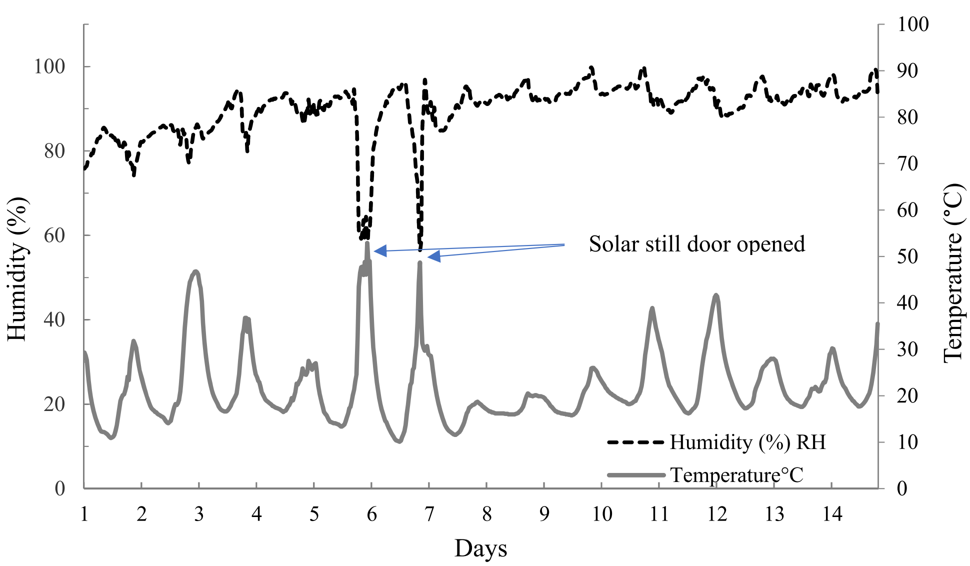

Fig. 9. Humidity (%) and temperature (°C) measured inside the solar still with temperature and humidity data logger.

manure layer requires further investigation and reducing the depth from 4 to 6 cm to 1 cm could potentially increase the drying rate Table 1.

3.3. Distillate analysis

The number of total coliforms and *E. coli* were very high in the distillate sample with the number of total coliforms measured at >242,400 per 100 ml and number of *E. coli* measured at 8010 per 100 ml (Table 2.). The number of *E.coli* present in the unfiltered samples is within the maximum limit (≤10,000 *E.coli* number/100 ml) for irrigation water according to European regulation [57]. The European union classifies reclaimed water with *E. coli* number ≤10,000 as Class D which can only be used on industrial, energy or seeded crops. The temperatures required to kill or inactivate bacterial pathogens are approximately 65 °C and at no point during the experiment did temperatures in the still reach this temperature. Previous studies have shown still internal temperatures reaching 62 °C [51], 54 °C [16] and 93 °C [58]. Haralambopoulos et al. [16] recorded a maximum sluge temperature of 57 °C, however, the counts of bacteria in the distillate were not recorded and the authors concluded that the distillate was "useless for further usage" due to contamination of the distillate by volatile organic compounds. A solar still constructed out of more suitable materials such as glass instead of polycarbonate and increasing the incidence angle could potentially increase the internal still temperature and if temperatures of approximately 65 °C are reached this would reduce the number of bacteria. The low solar irradiance and low hours of sunshine in the UK compared to other countries also negatively affect the internal still temperature (Tables 3 and 4).

Total coliforms in the distillate remained the same but in the filtered sample *E. Coli* increased to 18,290 per 100 ml, over double the number in the distillate. Downward gravitational flow was used to filter the distillate which caused the sample to remain in the filter for a longer period of time and could have allowed the bacteria already in the sample to multiply during this time. Down-flow configuration used in this study also creates the possibility of preferential flow in the biofilters [35]. Overall, the biofilter system used in this study did not reduce the number of bacteria.

The pH of the distillate was measured at 7.6, a value acceptable for drinking water, as drinking water is usually in the range 6.5–9.5 [59]. Filtered distillate recorded a higher pH of 8.44 ± 0.03. This alkaline value is most likely due to the alkaline nature of the sand and biochar used in the filter. Geomedia is usually sterilized prior to filter experiments, by rinsing in deionised water or acid washing and autoclaving at 121 °C, 100 kPa, for 15 min [39] however the biochar used in this study was not sterilized. Acid washing would remove the alkaline salts from the biochar and would ultimately have resulted in a lower pH value. The higher electrical conductivity value recorded for the filtered sample is also due to the salts in the biochar.

Table 3
Specification table of instruments used during experimental work.

Parameter measured	Instrument make and model	Specifications
External temperature and solar intensity	HOBO MX2202 lux and temperature data logger.	Waterproof to 30 m (100 feet) - +- 0.5 C (+- 0.9 F) accuracy Temperature sensor range: in air −20 to 70 °C Light sensor range: 0 to 167,731 lux (15,582 lum/ft2) - Accuracy: +- 10% typical for direct sunlight
Internal temperature and humidity	Elitech multi-use temperature and humidity data logger RC-51H model.	Humidity Range 10~95%RH Humidity Resolution 0.1%RH Humidity Accuracy: ±3%RH (25 °C, 20%RH 90% RH); other ±5%RH Temperature Accuracy: ±0.5 °C(20 °C~+40 °C); ± 1 °C (other range) Temperature Resolution: 0.1 °C Temperature Range: −30 °C~+70 °C
pH	Voltcraft pH metre	Measurement accuracy pH: 0.2 pH. Measurement range pH value: 0 – 13 pH. Resolution 0.01 pH Operating temperature: 0 to 50 °C
E. Coli	IDEXX Quanti-tray 2000	Detects down to one organism per 100 mL. 95% confidence limits better than 5- or 10-tube Most Probable Number (MPN). 95% confidence limits better than or comparable to membrane filtration (MF).
Total coliform	IDEXX Colilert-18/Quanti-Tray	Suppresses up to 2 million heterotrophs per 100 mL. Detects a single viable coliform or E. coli per sample.
Total nitrogen	Chemiluminescent detector Analytical Sciences Ltd, Thermalox model.	Lower Detection Limit of 50 ppb Upper Detection Limit of 200 ppm Selectively measures only Nitrogen Complete recovery of Nitrogen, including suspended solids

Table 4
Chemical properties of distillate water and filtered water.

Parameter	Distillate	Filtered
Electrical Conductivity µS/cm	781 ± 1.4	1316 ± 18.0
pH	7.60 ± 0.01	8.44 ± 0.03
TDS (total dissolved solids) ppm	370 ± 22.6	658 ± 33.5
Total coliforms per 100ml	>242,400	>242,400
Escherichia Coli per 100ml	8010	18,290
Turbidity NTU	11.4	4.0
NH_4 mg/l	127.9	107.6
$N(NO_2)$ mg/l	0.000	0.000
$S(SO_4)$ mg/l	0.59	28.73
$P(PO_4)$ mg/l	0.20	1.06
F mg/l	0.10	0.53
Cl (mg/l)	6.30	12.75

Total dissolves salts (TDS) of the distillate were measured at 370 ± 22.6 mg/L which is the range of acceptable concentrations of drinking water according to the US Environmental Protection Agency with a TDS limit of 500-mg/L and the World Health Organization with a TDS maximum of 1000 mg/L [60]. The increase in TDS (658 mg/L) after filtration is again due to the dissolved salts in sand and biochar in the biofilter.

The distillate collected looked very clear and recorded a turbidity of 11.4 NTU whereas the filtered sample recorded a lower turbidity of 4.0 NTU. Therefore, the biofilter was effective in reducing the turbidity of the distillate. For irrigation water a turbidity of <5 is the guideline for Class A water which can be used on all food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw according to European regulation [57]. There are no maximum turbidity limits for crops in Class B and C which are defined as crops that can be consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals [57].

The distillate contained relatively high concentration of ammonium NH_4 at 127.9 mg/l. This indicates that the distillate could be used potentially in agriculture as a form of liquid fertilizer perhaps in combination with biochar as a soil amendment.

The filtered sample contained five times more phosphorus (PO_4) than the distilled sample indicating that phosphorus within the biochar was taken up by the sample as it flowed through the biofilter.

Fluorine and chlorine levels were both higher in the filtered samples which could be due to impurities in the sand used and possible chlorine salts within the biochar. Acid washing and autoclaving the biofilter media would have prevented this. A parameter not measured was odour, however it was observed the distillate samples had a strong sweet odour, an indicator of high VOC content (volatile organic compounds). It was observed that the filtered sample was not as odoriferous, therefore it is likely that the biofilter removed some VOCs from the sample. This is consistent with previous work showing that biochar can efficiently remove VOCs from water [61].

These findings indicate overall that further research into the design of a solar still for drying dairy manure is necessary. Temperatures inside the solar still peaked at 52.9 °C. An increase in temperatures is required to destroy pathogens which are denatured at temperatures generally exceeding 65 °C. However, some modifications to the solar still could increase internal temperatures such as the use of thicker insulation materials, a glass cover of lower thickness [62] and altering the dimensions to achieve a higher incidence angle. The drying rate of the cow manure could be increased by spreading the manure to a thinner depth. If temperatures of >65 °C can be achieved with these modifications the resultant distillate would contain far fewer pathogens.

4. Conclusion

The simple solar still utilized in this study reduced the moisture content of 10 kg of dairy manure by 13%. The maximum temperature inside the still was recorded at 52.9 °C with a corresponding humidity of 57%. The biofilter technique used in this study did not reduce number of *E. coli* or total coliforms present in the distillate, however there was a reduction in turbidity from 11.4 NTU to 4.0 NTU. *E. coli* numbers present in the distillate prior to biofiltration were measured at 8010 per 100 ml which is within EU guidelines for irrigation water permitted for use on industrial, energy and seeded crops. Solar stills present a low energy, low economic alternative to reduce moisture content of animal waste prior to pyrolysis treatment.

Future work is required to determine optimum conditions and design parameters of a solar still for the drying of dairy manure with a focus on increasing internal still temperatures and reducing manure volume. Modifications to the biofilter design including trialling different flow regimes, should be conducted to determine how bacteria count and volatile organic compound content can be reduced in the distillate. This case study reveals that water captured from drying dairy manure in a solar still has potential to be re-used as irrigation water in agriculture.

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Declaration of Competing Interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Hannah Larissa Nicholas: Methodology, Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Supervision. **Ian Mabbett:** Supervision, Funding acquisition, Writing – review & editing.

Data availability

The data that support the findings of this study are available on request.

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