

An Effective Passive Solar Dryer for Thin Layer Drying of Poultry Manure

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Received 2012-07-30, Revised 2012-08-02; Accepted 2012-08-04

ABSTRACT

Animal and poultry manures have been recognized for centuries as organic fertilizers providing essential nutrients to crops and improving soil structure due to their large input of organic matter. Increasing demand for poultry and egg products has led to intensification of the poultry rearing process, resulting in large amounts of poultry manure. Drying can be used to reduce the environmental impact of poultry manure and create a value added product for the farmers (animal feed or organic fertilizer). The aim of this study was to investigate the effect of solar heated air drying on the chemical and biological characteristics of poultry manure and develop a suitable manure solar dryer. The effects of temperature (40-60°C) and manure layer depth (1-3 cm) were evaluated. At the three temperature levels studied, the time required to dry poultry manure in the 1 cm-deep layer was the shortest, followed by the 2 and 3 cm-deep layers, respectively. The optimum depth to dry manure (at which the highest drying effectiveness occurred) was 3 cm. The manure drying rate increased with increasing temperature and was the fastest at 60°C for all manure depths studied. A drying temperature-depth combination of 60°C and 3 cm was the most efficient for the thin layer drying of poultry manure. Drying poultry manure at these conditions provided an effective means of removing moisture and odor and destroying microorganisms, thereby allowing the production of a value added product. This temperature range is feasible with a solar dryer operating in the tropics. A solar dryer operating at a 3 cm manure depth would be capable of drying 336 kg/h. Drying poultry manure with solar heated air resulted in a slight decrease in protein content (from 42 to 41%), a decrease in pH (from 8.4 to 6.6), removal of *Salmonellae* and a 99% reduction in numbers of total bacteria, yeast, mold and *E. coli*. Thin layer solar drying of poultry manure proved to be an effective means of converting poultry manure into a value added product while reducing the environmental and health problems that are associated with current disposal options.

Keywords: Poultry Manure; Solar Drying; Solar Radiation; Mass and Heat Balance; Odor; Pathogens; Nutrients; Moisture Content

1. INTRODUCTION

Animal and poultry manures have been recognised for centuries as organic fertilizers providing essential nutrients to crops and improving soil structure due to their large input of organic matter. However, the increasing production of animal and poultry products to meet the demands of an ever increasing population has

resulted in large livestock and poultry operations that produce large amounts of manure making its storage and disposal an environmental and health problem. Improper handling and disposal of manure can cause air, water and soil pollution, result in

spreading of animal pathogens, deteriorating habitat and eliminating biodiversity (Benali and Kudra, 2002).

The economics of scale in livestock and poultry production have resulted in increased animal and bird densities that created manure management challenges for farmers and scientists throughout the world. This issue is particularly pressing with poultry production facilities as their farms typically manage little or no crop land and the produced manure poses serious environmental problems. As a result, the poultry industry is facing challenges related to the treatment and disposal of manure as the public is becoming less tolerant of environmental problems (Fugere *et al.*,

2007). Poultry manure begins to decompose immediately after excretion giving off ammonia which, in high concentrations, can have adverse effects on the health and productivity of birds as well as health of farm workers (Zhang and Lau, 2007; Amon *et al.*, 2006). Manure can also serve as a breeding ground for pathogenic microorganisms as well as a medium for disease transmission among birds. Flies and other undesirable insects can breed on manure leading to health hazards and nuisances associated with them (Lay *et al.*, 2011; Axtell, 1999). Manure is also a source of odor caused by the activity of microorganisms in the manure (Berry and Miller, 2005; Fares *et al.*, 2005).

Furthermore, manure cannot be applied onto frozen land in Canada and must be stored for 6-8 months. Organic acids produced by fermentation during manure storage have been implicated in the inhibition of seed germination (Iannotti *et al.*, 1994). Also hydrogen sulfide and greenhouse gasses such as methane and nitrous oxide are produced during storage (Brock and Madigan, 1991; Choi *et al.*, 2001; Pel *et al.*, 1997). It is, therefore, necessary to subject poultry manure to some treatments in order to improve its storage and handling properties and to minimize the risk of disease transmission and environmental pollution. Proper poultry manure management systems that will preserve the environment, contribute to animal and human health and return a profit on investment to farmers need to be developed.

Drying can convert poultry manure into a safe product that can be used as organic fertilizer or animal feed (Thomas *et al.*, 1972; Alam *et al.*, 2008). By drying, deterioration from chemical and biological activity is minimized and the environmental problems associated with decomposition of raw manure can be prevented. Drying also removes manure stickiness and hence makes its handling easier (Bernhart and Fasina, 2009). Drying with heated air offers a number of advantages over unheated air drying including: higher rate of oxidation and destruction of pathogens (Cummings and Jewell, 1977).

Drying with heated air can be carried out using a variety of heat sources such as solar energy, natural gas, or other fossil fuels. However, solar energy offers several advantages over other energy sources: (a) it is available in abundance all year round, (b) it has a higher rate of oxidation, (c) it results in good odor control and waste stabilization and (d) it has a higher rate of pathogen destruction (McCaskey and Wang, 1985; Amine-Khodja *et al.*, 2006; Martens and Bohm, 2009). Properly designed solar drying systems must take into account the drying requirements for specific products, energy efficiency and cost effectiveness (Tiris *et al.*,

1994; Diamante and Munro, 1993; Nellist, 1987).

The main objectives of this study were to: (a) determine the optimum drying rate of laying hen manure at a temperature range of 40-60°C and manure layer depth in the range of 1-3 cm, (b) determine the changes in the manure properties due to drying and (c) design a passive solar manure dryer.

2. KINETICS OF SOLAR MANURE DRYER

The abundant supply of solar energy could be used to provide the energy required to dry poultry manure and thus reduce the pollution problems associated with manure disposal. The most important element in a solar dryer is the solar collector which determines the amount of heat energy that may be trapped from the sun for the drying operation and the amount of water to be removed from the manure on a daily basis.

2.1. Mass Balance

If an amount of manure (W_m) at initial moisture content (M_i) and temperature (T_i) is to be dried to a final moisture content (M_f) at a temperature (T_f) in a given time (t), the manure feed rate (W_r) into the dryer can be calculated as follows:

$$W_r = \frac{W_m}{t} \quad (1)$$

Where:

W_r = The manure feed rate (kg/d)

W_m = The amount of manure to be dried (kg)

T = Time (d)

The amount of moisture entering the system daily (W_w) is calculated as follows:

$$W_w = \frac{M_i W_r}{100} \quad (2)$$

Where:

M_i = Initial moisture content (% wet basis)

W_w = Amount of moisture entering the system (kg/d)

The amount of dry matter (W_s) that passes through the system is calculated as follows:

$$W_s = W_r \left(1 - \frac{M_i}{100} \right) \quad (3)$$

Where:

W_s = Amount of dry matter entering the system (kg/d)

Hence, the amount of moisture to be removed (M_r) is calculated as follows:

$$M_r = W_r \left(\frac{M_i - M_f}{100} \right) \quad (4)$$

Where:

M_r = Amount of moisture to be removed (kg/d)

M_f = Final moisture content (% wet basis)

2.2. Heat Balance

The heat energy required for drying can be determined as follows:

$$\text{Heat required} = \left[\begin{array}{l} \text{Heat required to rise} \\ \text{the temperature of dry} \\ \text{matter from } T_i \text{ to } T_f \end{array} \right] + \left[\begin{array}{l} \text{Heat required to raise} \\ \text{the temperature of} \\ \text{moisture from } T_i \text{ to } T_f \end{array} \right] + \left[\begin{array}{l} \text{Heat required to} \\ \text{evaporate the moisture} \\ \text{at temperature } T_f \end{array} \right] \quad (5)$$

Mathematically, Eq. 5 can be written as follows:

$$Q = W_r \left[C_{p_s} \left(1 - \frac{M_i}{100} \right) + C_{p_w} \frac{M_i}{100} \right] (T_i - T_f) + h_v \left(\frac{M_i - M_f}{100} \right) \quad (6)$$

Where:

C_{p_s} = specific heat capacity of dry matter (KJ/kg°C)

C_{p_w} = specific heat capacity of water (KJ/kg°C)

h_v = latent heat of vaporization of water at temperature T_f (KJ/kg)

Q = heat energy requirement (KJ/day)

T_i = initial temperature (°C)

T_f = Final temperature (°C)

If the heat energy required for drying is to be met completely by solar radiation, then:

$$Q = H_\beta A_c \quad (7)$$

Where:

A_c = solar collector area (m²)

H_β = average solar radiation incident on a surface tilted at an angle β to the horizontal (KJ/m² d)

β = slope of collector (degrees)

Equation 7 can be rewritten as follows:

$$A_c = \frac{Q}{H_\beta} \quad (8)$$

The incident solar radiation H_β is estimated from the following equation (Duffie and Beckman, 1980):

$$H_\beta = H_b R_b (\overline{\tau_\beta})_{b,c} + (H_d R_s + H_p R_g) (\overline{\tau_\alpha})_{d,e} \quad (9)$$

Where:

H_b = estimated mean daily solar radiation on a horizontal surface (KJ/m² d)

H_d = estimated mean daily diffuse solar radiation on a horizontal surface (KJ/m² d)

H_p = measured mean daily total solar radiation on a horizontal surface (KJ/m² d)

R_b = correction factor for beam radiation on tilted surface (ratio of radiation on tilted surface to radiation of horizontal surface)

R_g = corrected factor for ground reflected radiation

R_s = correction factor for sky reflected diffused radiation = $(1 + \text{Cos}\beta)/2$

$(\overline{\tau_\beta})_{b,c}$ = mean daily effective transmittance absorptance product for beam radiation

$(\overline{\tau_\alpha})_{d,e}$ = mean daily effective transmittance absorptance product for diffuse radiation

ρ = surface albedo = $(1 - \text{Cos}\beta)/2$

Cairo lies on latitude 30° 2' N and longitude 31° 13' E. The mean daily solar irradiation on a horizontal surface in Cairo varies between 11.94 MJ/m²/d in December to 27.3 MJ/m²/d in June. Daylight duration varies from 11.68 hours in mid-December to 12.56 hours in mid-June with about 300 days per year of clear sky. The measured mean daily total solar radiation on a horizontal surface H_p was taken as 11.94 MJ/m²/d which represents the yearly minimum monthly average daily solar radiation on a horizontal surface. H_d was estimated from H_p using the method of Liu and Jordan (1960). H_b was determined as the difference between H_p and H_d . R_b , R_g , R_s , $(\overline{\tau_\beta})_{b,c}$ and $(\overline{\tau_\alpha})_{d,e}$ were determined according to the method given by Duffie and Beckman (1980). The initial temperature of the manure (T_i) was assumed to be equal to the ambient temperature (30°C).

Table 1. Parameters used in the estimated of collector size.

Parameter	Value	Comments
H	11.49 MJ/m ² d	Yearly minimum average daily total radiation on a horizontal surface
H _b	5.29 MJ/m ² d	Estimated from H
H _d	6.65 MJ/m ² d	Estimated from H
H _p	11.94 MJ/m ² d	Average daily extra-terrestrial radiation on a horizontal surface for August in Cairo
Ø	6.52°	Latitude for Cairo
β	7.0°	Slope of collector
D _s	13.45°	Solar declination
R _b	0.9628	Calculated
R _s	0.9963	Calculated
R _g	0.004	Calculated
ρ	0.2	Ground albedo (vegetated ground)
η _{ac}	1.49	Refractive index for acrylic
K _{ac}	25.0	Extinction coefficient for acrylic
t _g	0.005 m	Glazing thickness
α	0.95	Absorptivity of manure assumed equal to absorptivity of black point
$\overline{(\tau_{\beta})_{b,e}}$	0.584	Calculated
$\overline{(\tau_{\alpha})_{d,e}}$	0.709	Calculated
H _T	7.68 MJ/m ² d	Calculated
M _i	79.5% (wb)	Initial moisture content of manure
M _f	14% (wb)	Final moisture content of manure
T _i	30°C	Initial temperature of manure
T _f	60°C	Final temperature of manure
C _{p,w}	4.19 KJ/kg°C	Specific heat capacity of water
C _{p,s}	4.19 KJ/kg°C	Specific heat capacity of manure (assumed equal to that of water)
h _{fg}	2357.63	Latent heat of vaporization of water at 60°C
W	10 kg/d	Manure loading rate
Q	19.13 MJ/d	Daily heat requirement

The final (drying) drying temperature (T_f) was assumed to be 60°C based on flat plate collector absorber temperature records given by El-Sayed (1992). A summary of the parameters used in the estimation of collector area in Eq. 8 are shown in Table 1.

3. MATERIALS AND METHODS

3.1. Trays

Three sets of trays, each consisting of three trays of the same dimensions, were constructed using galvanized metal sheets for the drying of poultry manure in the laboratory. Each tray had a drying surface areas of 100 cm². The depths of the trays were 1 cm, 2 cm and 3 cm for sets 1, 2 and 3, respectively. Fig. 1 shows the dimensions of the drying trays.

3.2. Manure

Poultry manure was obtained from a layer house on Archibald Farms located in Stewiack East, approximately 80 km from Halifax, Nova Scotia. The manure was collected from under the battery cages of a laying house accommodating approximately 50,000 hens. The manure

collected was fresh and was not subjected to any treatment on the farm. It was placed in clean plastic bags and transported to the Waste Management Laboratory at Dalhousie University, Halifax, Nova Scotia where it was stored at -18°C. Some characteristics of the poultry manure used in this study are presented in Table 2.

3.3. Experimental Procedure

The effects of three drying temperatures (40, 50 and 60°C) and three manure depths (1, 2 and 3 cm) on the manure drying rate, drying time and manure characteristics were investigated. The selected temperature range is within the range (35 to 75°C) of heated air using solar dryers (El-Sayed, 1992). Prior to placing the manure in the drying trays, it was removed from the freezer and allowed to thaw for 24 hours at room temperature (22°C). The three sets of trays were weighed using a digital scale (METTLER Balance model PM4600, Fisher Scientific, Montreal, Quebec). The trays were then filled to their respective depths with the manure and weighed again. The filled trays were placed in a forced draft oven (Isotemp Oven Model 655F, Fisher Scientific, Montreal, Quebec) adjusted to the required temperature.

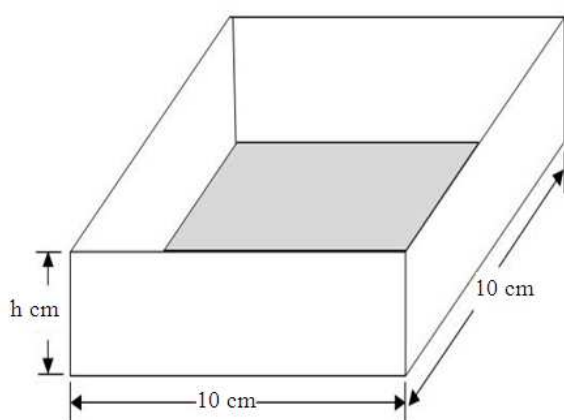


Fig. 1. The dimensions of the drying tray ($h = 1, 2$ or 3 cm)

The drying rate was monitored by determining the change in weight at 2 hour time intervals until a constant weight was reached. The oven temperature was then readjusted to the next required temperature and the same experimental procedure was followed. Three replicates for each temperature-manure depth combination were carried out.

3.4. Experimental Analysis

The moisture content, density, total and volatile solids, total and soluble chemical oxygen demand, total Kjeldahl and ammonium nitrogen, elemental (P, K, Ca), ash, total plate count, pathogen, insect, odor and pH analyses were performed on the raw manure. The moisture content, pH, protein, elemental, total plate count, pathogen and odor analyses were performed on the dried samples. The density, total solids and chemical oxygen demand analyses were performed according to the procedures described in the Standard Methods for Examination of Water and Wastewater (APHA, 1998). The total Kjeldahl and ammonium nitrogen analyses were performed using the Kjeltac Auto Analyser (Model 1030, Toecator, Hoganas, Sweden) according to the Kjeldahl method. The pH was measured using a pH meter (Model 805MV, Fisher Scientific, Montreal, Quebec) according to the procedure described in the Methods of Soil Analysis (ASABE, 2009). The elemental analyses (Ca, K, P) were performed in the Mineral Engineering Centre of Dalhousie University, Halifax, Nova Scotia, using flame atomic absorption spectroscopy. The moisture content, protein, microbial and odor analyses were performed as follows.

Table 2. Some characteristics of the poultry manure.

Item	Measured value
Moisture content	78.4 %
Density	960 kg/m ³
Total solids	215520 mg/L
Volatile solids	139770 mg/L
Ash	75750 mg/L
Total Chemical Oxygen Demand	328500 mg/L
Soluble Chemical Oxygen Demand	
Demand	130000 mg/L
Total Kjeldahl Nitrogen	18960 mg/L
Ammonium Nitrogen	9470 mg/L
Calcium	19760 mg/L
Phosphorous	5590 mg/L
Potassium	4140 mg/L
pH	8.40

3.4.1. Moisture Content

The moisture content was determined using the oven drying method according to the procedure described in the ASABE standards (ASABE, 2009). Samples of approximately 10 g were dried at 103°C for 24 h in a drying oven (Isotemp Oven Model 655F, Fisher Scientific, Montreal, Quebec) and the moisture contents (MC) were calculated as follows:

$$MC(\%wb) = \frac{(\text{Weight of wet sample} - \text{Weight of dry sample}) \times 100}{\text{Weight of wet sample}} \quad (10)$$

3.4.2. Odor

A specially developed organoleptic test for the measurement of odor from animal waste was used to measure the presence and offensiveness of odor in the dried poultry manure. This method was chosen because the complex nature of manure odor is best judged by the human nose. In this test, scales of 0-10 were used to rate the odor as to its presence and offensiveness. No odor was assigned a score of 0 and very strong odor was assigned a score of 10. Similarly, no offensive odor was assigned a score of 0 and very offensive odor was assigned a score of 10. The intermediate numbers 1-9 are described in the score sheet (Fig. 2) which was used by the panel members to rate the samples (50 g) placed before them in 125 Erlenmeyer flasks. The panel members were asked to rate the contents of the flasks according to the scales 0-10. The lower limit (0) was assigned to distilled water whereas the upper limit (10) was assigned to fresh poultry manure. The odor testing panel consisted of 10 members, including technicians, graduate and undergraduate students and faculty. Each panel member was asked to rate the samples as to the presence of odor and the odor offensiveness according to the 0-10 scales and to describe the odor on a separate data sheet.

Name: _____
 Date: _____

A. Rate the samples to the presence of odor and the odor as to offensiveness according to the following scale using samples "0" as having 0 rating and samples "10" as having 10 rating.

Presence		Offensiveness	
No odor	0	No offensive odor	0
Very faint	1-2	Very faint offensive odor	1-2
Faint	3-4	Faint offensive odor	3-4
Definite	5-7	Definite offensive odor	5-7
Strong	8-9	Strong offensive odor	8-9
Very strong	10	Very strong offensive odor	10

B. Describe the odor of each sample by giving an appropriate descriptive term. Possible terms that might be used are given in the list below or you may use a term of your choice which you feel properly describes the odor.

- | | |
|----------------------|----------------------------|
| Mold, musty | Yeast |
| Fish | Ammonia |
| Stagnant water | Grain, animal feed |
| Sulfide, rotten eggs | Sour, fermented |
| Petroleum | Rotten cabbage, mercaptans |
| Earth | Other (Please specify) |

RATING

Sample	Presence Rating	Offensiveness Rating	Odor Description
1			
2			
3			

Thank you for your time

Fig 2. Odor evaluation sheet (Ghaly and MacDonald, 2012)

3.4.3. Total Microbial Count

Total plate count was employed to estimate the numbers of viable aerobic and facultative microorganisms based on the assumption that each viable cell would develop into a colony after incubation. The manure samples were collected in wide mouth sterilized containers. Each sample was diluted to insure that one of the final plates would have 30 - 300 colonies (the range which allows the most accurate approximation of the microbial population). The initial dilution (1:10) was prepared by placing 1 g on manure into 10 mL of physiological saline water. The bottle was shaken vigorously to obtain a uniform distribution of organisms.

Further dilutions (1:10³, 1:10⁴, 1:10⁵, 1:10⁶, 1:10⁷ and 1:10⁸) were made by pipetting measured aliquots into physiological saline water. The bottles were thoroughly shaken and 1 mL of the dilution was pipetted into each labeled (specimen and dilution) petri dish. Samples from each dilution were plated in duplicate. Approximately 15 mL of cooled melted medium was poured into each petri dish. Immediately thereafter, the plates were gently rotated 6 times in each direction to distribute the inoculum throughout the medium. The plates were allowed to solidify and incubated in the inverted position in an incubator (Model Number 2020, VWR International, Cornelius, Oregon) at 35-37°C for 48 hours. Plates that contained 30-300 colonies were

selected for counting. An accurate count of the colonies was made by placing the plates on the platform of a colony counter (Cat.No.7-910, Fisher Scientific, Montreal, Quebec). This instrument facilitated the counting process since the colonies were illuminated and viewed against a ruled background. The number of colonies counted and the dilution of the specimen were used to calculate the cell count per milliliter of the specimen.

3.4.4 Microbial and Insect Analyses

The following analyses were also performed on the raw and dried manure samples: (a) yeast and mold enumeration (b) *E. Coli* estimation and (c) *Salmonellae* examination. These analyses were performed at Nova Scotia Research Foundation Corporation, Dartmouth, Canada.

3.4.5 Protein

The total protein content was determined using the Tecator Kjeltac Auto Analyser (Model-1026, Fisher Scientific, Montreal, Quebec). Clean empty tarred beakers were weighed (W_1) and approximately 1.0 g of the manure samples (or about 0.5 g of dried samples) was placed in each of the beakers and reweighed (W_2). The contents of the beakers were then transferred to macro 250 mL digestion tubes. One "Kjeltab" (containing 3.5 g K_2SO_4 and 0.0035 g Se), 3.0 mL of distilled water (H_2O), 0.6 mL of concentrated sulphuric acid (H_2SO_4) and 0.3 mL of 30% hydrogen peroxide (H_2O_2) were added to the samples in the digestion tubes. The samples were digested at 420°C for 30 minutes in a digestion block heater (Tecator Digester Sytem, 20 Model-1016, Fisher Scientific, Montreal, Quebec). The digestion tubes were removed and allowed to cool for 10 minutes. Then, 30 mL of distilled water were added to the digestion tubes. The test tubes and digests were transferred to the Auto Analyser. The constants A and B for the equipment were set at 0.00 and 1.862, respectively. The titrant acid and the predetermined

blank sample were set at 0.2127 M and 0.01, respectively. Distillations, titrations and calculations were performed automatically. The protein percentage was computed from the following equation:

$$\text{Total protein (\%)} = \frac{\text{Displayed results}}{W_2 - W_1} \quad (11)$$

4. RESULTS AND DISCUSSION

4.1. Drying Time

The results (Table 3) indicated that the 1 cm deep manure layer dried the fastest at all three drying temperatures, followed by the 2 and 3 cm deep manure layers, respectively. The thinner the manure layer, the lower the amount of moisture it contained and consequently the shorter the time required to drive off the moisture. The times required to dry the 2 cm deep manure layers were more than the time required to dry the 1 cm deep manure layers by about 106%, 100% and 87% while the times required to dry the 3 cm deep manure layers were more than the times required to dry the 2 cm deep manure layer by 22%, 12% and 7% at temperatures of for 40, 50 and 60°C, respectively.

The effect of bed depth on drying rate was investigated by several researchers. Nazghelichi *et al.* (2010) investigated the effect of bed depth (30, 60 and 90 mm) on the drying of carrot cubes and found the shortest drying time to be achieved at the 30 mm depth. Maskan *et al.* (2002) investigated the effect of layer thickness (0.71-2.86 mm) on the drying of fruit leather at various temperatures and air velocities and found the optimum depth to be 0.71 mm. Ertekin and Yaldiz (2004) investigated the effect of slice thickness (0.63, 1.27, 2.54 cm) on drying of eggplant and reported the fastest drying times with the 0.63 cm thick slices. The trends reported by these researchers are similar to those obtained in the present study.

Table 3. Drying time and drying effectiveness of poultry manure.

Drying Temperature (°C)	Drying Depth (cm)	Drying Time (h)	Weight (g)		Moisture (g)	Drying Effectiveness (h/g)
			Initial	Final		
40	1	55	125.95	27.15	98.80	0.56
	2	106	224.70	48.43	176.27	0.60
	3	120	312.72	67.41	245.31	0.50
50	1	44	129.16	27.84	101.32	0.43
	2	84	226.21	48.71	177.50	0.47
	3	90	314.28	67.74	246.54	0.37
60	1	28	127.18	27.41	99.77	0.28
	2	52	227.86	49.11	178.75	0.29
	3	60	322.57	69.52	253.05	0.24

Several researchers also studied the effect of drying temperature on the drying rate of various materials and reported faster drying rates at higher temperatures. Leonard *et al.* (2005) investigated the effect of temperature (120, 140 and 160°C) on the drying rate of municipal sludge and reported the fastest rate of drying at 160°C. Onider *et al.* (2010) studied the drying kinetics of rough rice at varying temperatures (19-26°C) and observed the fastest drying rate at the highest temperature (26°C). Panchariya *et al.* (2002) studied thin layer drying of black tea at various temperatures (80-120°C) and reported the fastest drying rate at the highest temperature (120°C). Gely and Santalla (2007) studied the effect of temperature (50-90°C) on the drying rate of quinoa seeds and observed the highest drying rates at 90°C. Brooks *et al.* (2008) investigated the effect of temperature (55 and 65°C) on the drying kinetics of tomato pieces of various geometries (whole, halves, quarters and eights) and found the fastest drying rates at 65°C for all geometries.

4.2. Drying Effectiveness

The drying effectiveness in this study is defined as the time required to drive off 1 g of moisture from the manure. The results (Table 3) showed that the difference in drying time between the shallower and deeper manure layers decreased as the temperature increased. However, when considering the drying effectiveness, the 3 cm manure depth was superior at all temperatures as less time was required to remove 1 g of water from the manure. The results also showed that more time was required to remove one gram of water from the manure at the 2 cm depth than those required at the 1 and 3 cm depths at all temperatures.

Ertekin and Yaldiz (2004) conducted a study into the thin layer drying of eggplant slices (0.63, 1.27 and 2.54 cm thick) and found the most effective drying with 2.54 cm thick slices. However, significant increases in the depth of bed have been reported to decrease drying effectiveness. Nazghelichi *et al.* (2010) investigated the effect of bed depth (30, 60 and 90 mm) on the drying effectiveness of carrot cubes and found the optimum drying efficiency at 30 mm depth. Rao *et al.* (2007) investigated the thin layer drying of parboiled paddy at depths between 5 and 20 cm and reported optimum effectiveness with the lower depths in the range of 7-10 cm. Akal *et al.* (2007) investigated the effect of bed depth (10-30 cm) and air temperature (40, 50 and 60°C) on the effectiveness of thin layer drying of rough rice

and found the effectiveness to decrease with increasing bed depth.

4.3. Odor

At the start of each experiment, the odor given off near the oven during the drying process was noticeable. However, as the drying process progressed, the presence and offensiveness of the odor decreased with the time and the final product (dried manure) did not have any offensive odor. The results (Table 4) of the organoleptic test performed on the dried manure (3 cm deep manure layer at 60°C) showed that both the presence and offensiveness of the odor were reduced by 65.3% and 69.3%, respectively. The odor present in the dried manure was not found to be offensive (23.3% of the panel members described the odor as that of grain, 20% described it as a mold musty, 13.3% described it as ammonia, 13.3% described it as sour/fermented, 6.7% described it as fish odor, 6.7% described it as yeast odor and 6.7% described it as sulfide/rotten eggs odor).

Welsh *et al.* (1977) reported a statistically significant decrease in odor after drying swine manure. Zhang *et al.* (2009) stated that the odor intensity was affected by the initial moisture content. They compared the odor emission in the initial phase of composting (24 hours) of broiler litter and found that nearly twice as much odor was emitted at the 75% moisture content compared to 40% moisture content. Liao and Liang (2000) developed a mass transfer model which demonstrated that lower odor emissions occur when manure moisture is reduced due to the reduced advection that decreased the release of volatile fatty acids from the manure. Carey *et al.* (2004) reported that poultry manure odor was linked to ammonia volatilization and could be eliminated through drying manure to a moisture content below 50%.

Table 4. Odor rating (manure dried at 60°C and 3 cm depth).

Parameter	Dried ^a	Fresh
Presence	3.47±1.25	10
ffsiveness	3.07±1.53	10
Description		
Grain, Feed	10	-
Mold, Musty	6	-
Sour, Fermented	4	-
Yeast	2	-
Earth	2	-
Fish	2	-
Ammonia	2	3
Sulphide, Rotten Egg	2	12
Stagnant water	-	12
Rotten Cabbage	-	3

* Total number of observations- 30

Table 5. Manure characteristics.

Parameter	Initial	Final ^a
Chemical Parameters		
Moisture Content (%)	77	14
TKN (mg/kg)	87970	39260
Organic N (mg/kg)	43940	30940
Ammonium N (mg/kg)	17450	8329
pH	8.4	6.6
Microbial Parameters		
Bacteria (10 ⁴ cells/g)	477000	620
Yeast & mold (cells/g)	2700	<10
<i>E. coli</i> (10 ⁴ cells/g)	2190	<10
<i>Salmonellae</i>	PD ^b	ND ^c
Nutritional Parameters		
Protein (g/kg)	43.32	41.59
Calcium (g/kg)	91.7	91.3
Phosphorus (g/kg)	24.8	24.5
Potassium (g/kg)	19.2	18.9
N P K	8.8,2.5,1.9	3.9,2.5,1.9

a Dried at 60°C and 3 cm depth

b Partially Detected

c Not Detected

4.4. Microbial Count

The results of the microbial analyses are shown in **Table 5**. High numbers of bacteria (477×10^7 cells/g manure) and yeast and mould cells (2700 cells/g manure) were found in the raw manure. The drying process (a 3 cm deep layer at 60°C) reduced the number of bacteria by 99.87% (from 477×10^7 to 620×10^4 cells/g manure), the yeast and mold cells by 99.63% (from 2700 cells/g to <10 cells/g) and *E. coli* by 99.56% (from 2290×10^4 cells/g to $<10 \times 10^4$ cells/g). *Salmonellae* was partially detected in the raw manure, but was not detected in the manure after drying at 60°C and 3 cm depth.

The metabolic activity, growth and survival of an organism are influenced by temperature and the killing action of heat is a time-temperature dependent process (Gradel *et al.*, 2003). Practical procedures by which heat is employed are divided into two categories: (a) moist heat and (b) dry heat. There is a considerable difference in the moist and dry heat killing efficiencies of microorganisms. Moist heat destroys microorganisms through the denaturation of cellular proteins, facilitated by the presence of moisture. In contrast, dry heat dehydrates the cell and destroys microorganisms through the oxidation of intracellular constituents (Cutter, 2002). Hence, dry heat (or hot air) sterilization is recommended where it is either undesirable or unlikely that pressurized steam will make direct and complete contact with material to be sterilized.

Chang *et al.* (1974) reported that aerobic and

anaerobic microbial counts were directly related to the moisture content of dehydrated cage layer samples and inversely related to the dehydration temperature. The authors observed that the aerobic and anaerobic microbial counts could be significantly reduced if the moisture content of the sample was reduced to less than 10%.

Kim *et al.* (2012) studied the thermal inactivation of *Salmonellae* in broiler litter by dry heat and found that the temperature and moisture content affected the survival of *Salmonellae* in the litter. They found the time required for a 7 log reduction in *Salmonellae* at 30% moisture content to be 80, 78 and 44 min for the 70, 75 and 80°C drying temperatures, respectively. When the initial moisture content of the broiler litter was increased from 30 to 50%, the time required to achieve a 7 log reduction was increased to 100, 93 and 63 min at 70, 75 and 80°C drying temperatures, respectively.

Watcharasukarn *et al.* (2009) evaluated the efficiency of pathogen removal by dry heat in dairy manure and found that *E. coli* was the most heat susceptible of the three organisms tested (*E. coli*, *E. fecalis*, *C. perfringens*). Sterilization (defined as a 10 log reduction in viable cell count) times were found to be 5 d, 40 min and 10 s at 37, 55 and 70°C, respectively.

Elving (2009) observed a 3 log reduction in the *E. coli* content of dairy manure after using dry heat for 60 min at 70°C. The time needed for a 90% reduction in bacterial count was of 4.3, 1.5 and 0.5 h at 49, 52 and 55°C respectively for *Salmonellae*.

4.5. Manure pH

Heated air drying at 60°C and 3 cm depth caused a drop in pH from the initial value of 8.4 to 6.6 as shown in **Table 5**. The reduction in the pH was due to the loss of ammonium through the volatilization process. Similar results were reported by other researchers. Lopez-Mosquera *et al.* (2008) observed a drop in pH (from 8.5 to 7.9) when drying poultry manure for pelletizing as fertilizer. Dikinya and Mufwanzala (2010) reviewed the literature and noticed lower pH values for dried poultry manure compared to those of fresh poultry manure. Sistani *et al.* (2001) investigated the changes in broiler litter pH after air drying, hot air drying (65 and 105°C) and freeze drying and observed that hot air drying at 105°C resulted in a significant drop in manure pH.

4.6. Total Protein Content

The results (**Table 5**) showed the total protein concentration of the dried manure (60°C and 3 cm depth) was 3.99% lower (reduction from 43.32 to 41.59 g/kg) than that of the raw manure.

Cullison *et al.* (1976) found crude protein contents of air dried broiler and hen manure to be 34.5 and 40.4%, respectively. However, other researchers reported much lower values. Torto and Rhule (1997) reported a decrease in crude protein content (27-20 %) in poultry manure after heated air drying (80°C) and sun drying. Gihad (1976) reported a final crude protein content of 22.06% after forced air drying at 65°C. El-Deek *et al.* (2009) dried poultry manure at 80°C and reported a final crude protein content of 19.10%. Obasa *et al.* (2009) sun dried poultry manure and reported a final protein content of 28.6%. The protein content of the dried poultry manure obtained in the present study is higher than the values reported in the literature, probably due to the lower drying temperature used in this study.

Protein is typically the largest and most expensive component of an animal diet. Protein provides the essential amino acids and nitrogen for the synthesis of non-essential amino acids and other nitrogen containing compounds (Snow and Ghaly, 2007; NRC, 1984). The dried poultry manure had a protein content of 422 g/kg which exceeds the recommended dietary intake of animals (7.3-7.8 g/kg) reported by the NRC (1984).

4.7. Elemental Analysis

The results (Table 5) showed minimal losses of 0.4% in calcium (from 90.7 to 90.13 g/kg), 1.2% in phosphorus (from 24.8 to 24.5 g/kg) and 1.6% in potassium (from 19.2 to 18.9 g/kg) due to drying of poultry manure at 60°C and 3 cm depth. These reductions are within the experimental errors. Patterson and Lorenz (1996) reported a slight increase in calcium content after air drying. Nicholson *et al.* (1996) reported an increase in phosphorus content of various poultry manures after air drying. The potassium content of dried poultry manure obtained in this study was in the range reported by Nicholson *et al.* (1996) and lower than that reported by Moreno-Caselles *et al.* (2002).

The total Kjeldahl nitrogen, organic nitrogen and ammonium nitrogen contents of the manure were reduced by 55.37% (from 87.97 to 39.26 g/L), 29.58% (from 43.94 to 30.94 g/L) and 52.26% (from 17.45 to 8.33 g/L), respectively as shown in Table 5. The large losses in nitrogen content were due to ammonia volatilization during the drying process. Similar results were reported by Nicholson *et al.* (1996). The total nitrogen content obtained in the present study is within the range of nitrogen contents reported by other researchers (Nicholson *et al.*, 1996; Lopez-Mosquera *et al.*, 2008; Moreno-Caselles *et al.*, 2002; Patterson and Lorenz, 1996).

Although the phosphorus and potassium contents remained relatively unchanged in the dried poultry manure, the loss of nitrogen during the drying process changed the NPK ratio of the poultry manure from 8.8: 2.5: 1.9 to 3.9: 2.5:1.9 (Table 5). The dried poultry manure NPK ratio in this study falls within the range of NPK ratios reported in the literature for dried poultry manure Patterson and Lorenz (1996) reported an NPK ratio of 1.8: 2.7: 1.6 for dried hen manure. The low nitrogen content (relative to the current study) may be due to the 4-6 week storage of poultry manure in the poultry houses before sampling, which allowed for increased volatilization of ammonia. Nicholson *et al.* (1996) reported poultry manure NPK ratios of 6: 2: 2 and 6: 2: 3 after air drying. Moreno-Caselles *et al.* (2002) reported an NPK value of 3.1: 3.0:3.0 for dried chicken manure.

Yavinder-Singh *et al.* (2009) reported improved growth to rice and wheat crops when fertilized with poultry manures with NPK ratios of 1.9: 1.6: 1.9. Poultry manures are preferred over other animal manures for use as fertilizers due to their higher contents of readily available potassium and phosphorus (Nicholson *et al.*, 1996; Moreno-Caselles *et al.*, 2002).

4.8. Drying Manure in a Solar Dryer

Assuming that the average temperature in the drying chamber is 60°C and the moisture content of the manure to be dried is 78.44% as in the experiment, the amount of manure that will be fed into the dryer using a 3 cm deep layer can be calculated as follows:

$$W_{D3} = \frac{A_{D3} \times W_{T3}}{A_{T3}} \quad (12)$$

Where:

W_{D3} = weight of manure to be fed into the solar dryer for a 3 cm deep layer (g)

A_D = surface area of the drying chamber in the solar dryer (cm²)

W_{T3} = weight of the manure in 3 cm deep drying tray (g)

A_{T3} = surface area of the 3 cm deep drying tray (cm²)

The manure index (D_M) is defines in this study as the amount of manure that can be dried per hour. D_M can be calculated for the 3 cm deep manure layer as follows:

$$D_{M3} = \frac{A_D \times W_{T3}}{A_T \times \theta} \quad (13)$$

Where:

- D_{M3} = the manure index for the 3 cm deep manure layer (kg/h)
- Θ = The time required to dry the manure in the 3 cm deep drying tray at 60°C (h)

In this study θ and D_{M3} were estimated to be 60 h and 336 kg/h, respectively. The required area was estimated from Eq. 7 and Eq. 9 as approximately 2.50 m². A rectangular collector of 2.1 m in length and 1.2 m in width (with an area of 2.52 m²) was selected and passive solar poultry manure dryer was constructed. The passive solar poultry manure dryer (Fig. 3) consisted of three components: the hopper, the feeding system and the drying chamber. In operation, the equipment is positioned with the width along the east-west axis and the solar collector facing south.

4.8.1 Hopper

The hopper was designed as a funnel shaped reservoir from which the manure is discharged on to the drying unit located at its base. It was made of 18 gauge galvanized sheet metal. The upper section of the hopper resembled a cube having dimensions of 120, 50 and 60 cm for the lengths, width and depth, respectively. Three of the sides were pop riveted together using 16 10 mm pop rivets, spaced 75 mm apart. The fourth side (removable section) was held in place with 6 machine screws, 3 placed equidistant on each end. The lower section of the hopper had dimensions at the bottom end of 120, 10 and 40 cm for the length, width and depth, respectively. The angle of incline of the lower section of the hopper was 28° to the vertical. The bottom was closed with a sliding gate that was manually opened during feeding.

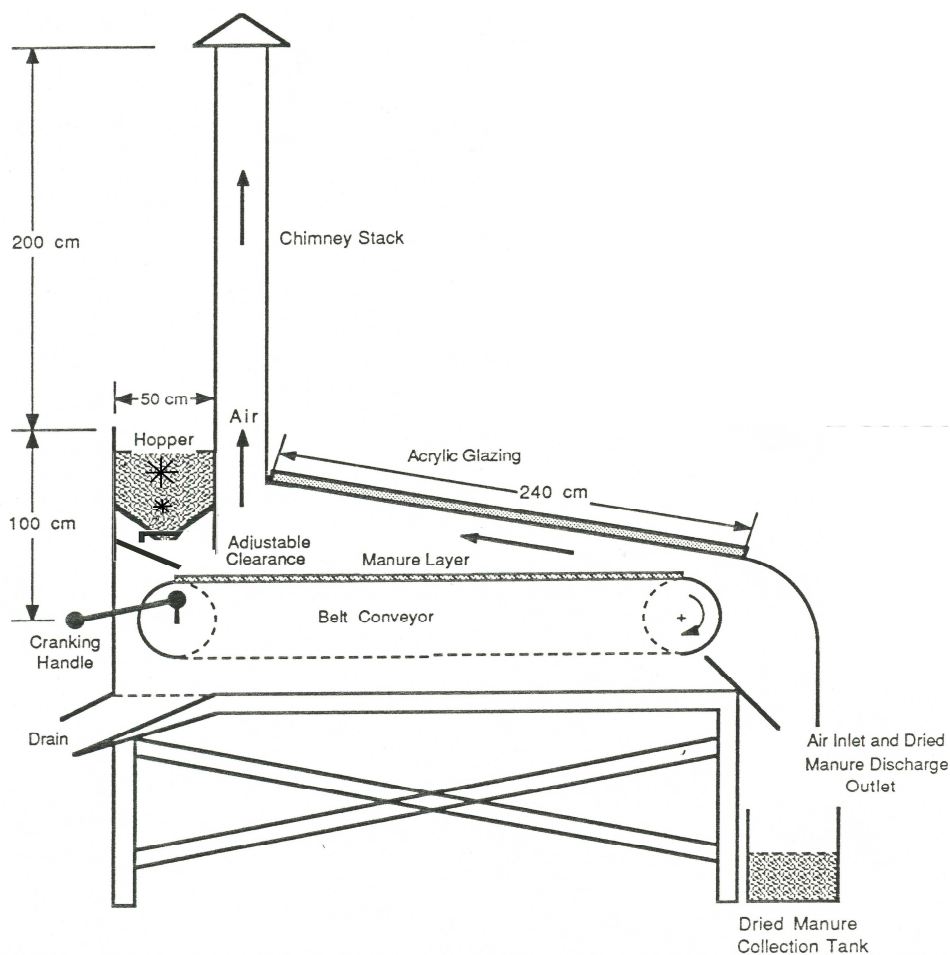


Fig. 3. A passive solar manure dryer

The biggest problem that was encountered during operation was the difficulty of feeding manure freely into the dryer without applying force on the manure which also compressed the manure and made it difficult to press through. Use of agitators was found to be necessary to prevent manure from settling and consolidation in the hopper. Therefore, two agitators were used to loosen and mix the manure in the hopper in order to keep it homogeneous and easily flowing. The agitators were made of 25 mm diameter steel shaft with wire wrapped around them 4 turns and extended to form spikes as shown in Fig. 4. There were small holes drilled in the end of the shaft for the wrapped ends of the wire to prevent them from rotating around the shaft. As the force of resistance of the manure tries to wrap the wires around the shaft, the wires tighten themselves onto the shaft. The upper agitator had 8 music gauge wires extending 17 cm radially whereas the lower agitator had 9 music gauge wires extending 8 cm radially. To support the agitator shafts at the end, non-expansion 2-bolt pillow blocks (lubricated with grease) were used. These pillow blocks were bolted onto horizontal angle iron supports using two 14 mm x 50 mm UNC bolts and hex nuts each.

4.8.2 Feeding System

The feeding system consisted of two sets of chains mounted on two pairs of sprockets on both sides of the dryer. The chain links were interconnected by a series of flat galvanized steel slats that form the drying bed.

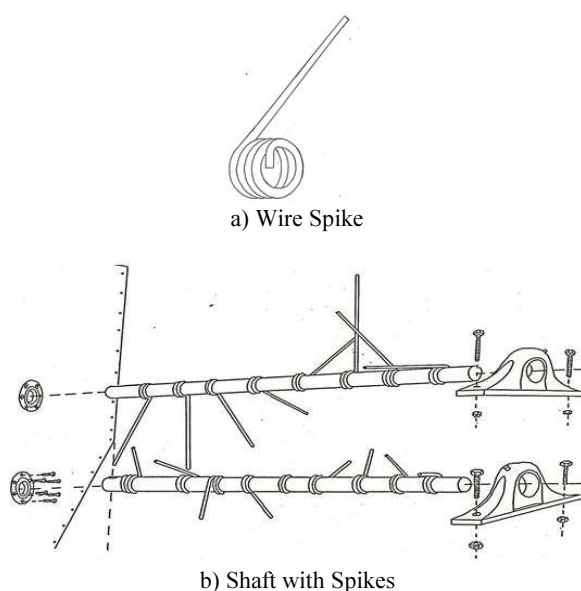


Fig. 4. Manure agitators

The chain slats passed just below the base of the hopper and into the drying chamber. The slats were moved manually using a crankshaft with a handle to rotate the sprockets. One of the sprockets was connected to the agitators by chains. At the end of each drying batch, cranking of the handle allowed for the discharge of the dried manure through the outlet into the manure collection bucket, while recharging the drying chamber with a fresh batch of homogeneous manure from the hopper.

4.8.3 Drying Chamber

The drying chamber consisted of the drying bed of chain slats over which an acrylic glazing of 216 cm long, 120 cm wide and 0.6 mm thick was mounted. A chimney stack of 25 cm diameter and 200 cm height with an air inlet was provided. The difference in temperature between the air in the drying chamber and the ambient air induced air flow by natural convection. This facilitated the removal of moisture that evaporated from the manure in the drying chamber.

5. CONCLUSION

At the three temperature levels studied, the time required to dry poultry manure in the 1 cm-deep layer was the least, followed by the 2 and 3 cm-deep layers, respectively. The optimum depth to dry manure (at which the highest amount of moisture is removed in the shortest amount of time) was 3 cm. The manure drying rate increased with increasing temperature and was the fastest at 60°C for all manure depths studied. A drying temperature-manure depth combination of 60°C and 3 cm was the most efficient for the thin layer drying of poultry manure. Drying poultry manure at 60°C and 3 cm depth provides an effective means of removing moisture and odor and destroying microorganisms, thereby enabling the production of a value added product. This temperature range is feasible with a solar dryer operating in the tropics. Based on the heat and mass analyses, a solar dryer operating at a 3 cm depth and 60°C would be capable of drying 336 kg/h. Drying poultry manure with solar heated air resulted in a slight decrease in protein content (from 42 to 41%), a decrease in pH (from 8.4 to 6.6), total removal of *Salmonellae* and a 99% reduction of bacteria, yeast, mold and *E. coli*. Thin layer solar drying of poultry manure proved to be an effective means of converting poultry manure into a value added product (organic fertilizer or animal feed) while reducing the environmental and health problems associated with current disposal options.

6. ACKNOWLEDGEMENT

This research was funded by the Natural Science and Engineering Research Council (NSERC) of Canada.

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