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Research article

Moisture content prediction in poultry litter using artificial intelligence techniques and Monte Carlo simulation to determine the economic yield from energy use

José Octavio Rico-Contreras*, Alberto Alfonso Aguilar-Lasserre, Juan Manuel Méndez-Contreras, Jhony Josué López-Andrés, Gabriela Cid-Chama

Division of Research and Postgraduate Studies, Instituto Tecnológico de Orizaba, Av. Oriente 9 # 852, Col. Emiliano Zapata, 94300, Orizaba, Mexico

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ABSTRACT

The objective of this study is to determine the economic return of poultry litter combustion in boilers to produce bioenergy (thermal and electrical), as this biomass has a high-energy potential due to its component elements, using fuzzy logic to predict moisture and identify the high-impact variables. This is carried out using a proposed 7-stage methodology, which includes a statistical analysis of agricultural systems and practices to identify activities contributing to moisture in poultry litter (for example, broiler chicken management, number of air extractors, and avian population density), and thereby reduce moisture to increase the yield of the combustion process. Estimates of poultry litter production and heating value are made based on 4 different moisture content percentages (scenarios of 25%, 30%, 35%, and 40%), and then a risk analysis is proposed using the Monte Carlo simulation to select the best investment alternative and to estimate the environmental impact for greenhouse gas mitigation. The results show that dry poultry litter (25%) is slightly better for combustion, generating 3.20% more energy. Reducing moisture from 40% to 25% involves considerable economic investment due to the purchase of equipment to reduce moisture; thus, when calculating financial indicators, the 40% scenario is the most attractive, as it is the current scenario. Thus, this methodology proposes a technology approach based on the use of advanced tools to predict moisture and representation of the system (Monte Carlo simulation), where the variability and uncertainty of the system are accurately represented. Therefore, this methodology is considered generic for any bioenergy generation system and not just for the poultry sector, whether it uses combustion or another type of technology.

1. Introduction

The poultry industry is the second-largest meat-production industry in the world. It is a sector in constant growth, as it is linked to population growth and consequently an increase of agricultural waste. That is why poultry companies are constantly seeking areas of opportunity to make the broiler chicken production value chain more profitable. One of these areas is the energy use of poultry litter produced at the end of the production cycle.

Poultry litter is waste containing broiler chicken excreta mixed with rice hull, water, intestinal mucosa, feathers, and undigested feed, etc. Poultry litter is traditionally used as a food supplement for ruminants and as a raw material to produce compost. However, it includes organic substances that can be used to produce steam in boilers and subsequently electrical energy using a turbogenerator, offering an opportunity to substitute nonrenewal energy (McKendry, 2002a, 2002b). These actions can help reduce costs and increase the profitability of energy processes by applying better technologies in a sustainable manner (Taylor, 2008; Saidur et al., 2011), producing bioenergy and bioproducts such as biofertilizers (Sacramento-Rivero et al., 2010).

Some studies have placed special emphasis on moisture, as this determines the energy released in boilers and therefore the steam produced, so it should be used dry or its moisture should be reduced before combustion (Serio, 2003). Poultry litter with a moisture of 10% releases 2943 kcal/kg (Whitely et al., 2006), and applying the linear function 3495.9−32.6× the heating value (HV) is determined with different moisture levels (Dávalos et al., 2002).

* Corresponding author.
E-mail address: octaviorico@hotmail.com (J.O. Rico-Contreras).

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Nomenclature

h_g	Coefficient of latent heat of vaporization of water, expressed in kcal per kg
T	Temperature
$°C$	Degrees Celsius
$kcal$	Kilocalories
kg	Kilograms
LHV	Lower heating value, expressed in kcal/kg poultry litter
HHV	Higher heating value, expressed in kcal/kg poultry litter
M_R	Moisture content (%) in poultry litter, in real conditions
M_{BS}	Percentage (%) of moisture content in poultry litter, in experimentation conditions (dry basis)
ΔH_{vap}	Enthalpy output between output water and output steam, in kcal/kg
H_{Final}	Steam enthalpy at a pressure of 63.3 kg/cm^2 and a temperature of 445 °C, in kcal/kg. Obtained from Mollier water vaporization table or diagram
$H_{Initial}$	Steam enthalpy at a pressure of 75 kg/cm^2 and a temperature of 85 °C, in kcal/kg. Obtained from Mollier water vaporization table or diagram
d	Operating days per year
dc	Broiler chicken production cycle days
pe_{cycle}	Broiler chickens in production cycle
P_{yield}	Poultry litter yield per broiler chicken
tP	Tons of poultry litter available per year
CtP	Combustion capacity in tons of poultry litter per year
% Purchase	Purchase (%) of poultry litter in addition to those produced
%tmca	Average annual growth rate of poultry litter (%)
n_{cap}	Number of years (7) in which the plant will be operating at full capacity
%tm	Lost time (%) due to equipment maintenance
h_{efect}	Effective operating hours of the combustion system
cP_h	Hourly availability of poultry litter combustion
E_h	Energy available in poultry litter per hour (kcal)
tV_h	Tons of steam available per hour (temperature = 445 °C; pressure = 63.3 kg/cm^2)
$\%efic_{Boiler}$	Steam generating efficiency (%) in the boiler
RtV_h	Vapor generated per unit of poultry litter burned
CtV_h	Consumption of steam per hour for each MW-hour produced by the turbogenerator (ton)
pMW_h	Electrical energy production in Megawatts-hour in the turbogenerator
CI_{Boiler}	Installed capacity in each boiler
$35\%_{Clearance}$	Steam flow clearance upon receiving top-quality biomass and/or less moisture and which can support steam-generation peaks
$CI_{Turbogenerator}$	Turbogenerator nominal capacity
$\%efic_{Turbogenerator}$	Efficiency of a turbogenerator (%) that uses high-pressure steam

Moisture less than 25% can be burned without the need to use additional fuels (Abelha et al., 2003), achieving the ability to produce steam and electrical energy (Kelleher et al., 2002; Martin and Lefcort, 2002), and at the same time broiler chickens receive better health conditions and greater comfort inside the farm (Collet, 2012; Ferreira et al., 2012).

For these reasons, the technology selection process for poultry litter treatment should factor in all aspects related to poultry production (feeding, hydration, ventilation, etc.) in order to establish the benefits and risks associated to the bioenergy production (Quiroga et al., 2010; Sondreal et al., 2001).

In this sense, artificial intelligence (AI) tools have helped to predict the behavior of non-linear systems (Chen et al., 2008) and to control variables to improve the operating conditions of a system's environment (Batayneh et al., 2010; Das and Das, 2013; Lee, 2000). This is the case of fuzzy logic (FL), which uses inaccurate data and expertise (Zadeh, 2008), and artificial neural networks (ANN) that use real data sets for training (Lakhankar et al., 2006).

In industrial food-production processes, FL and ANN have been applied to control air temperature, atomization flow, and feeding flow in spray drying processes, making it possible to predict the physical properties of orange juice powder concentrate (Chegini et al., 2008). FL focuses on prediction based on specific conditions of the system. This is the case of Sablani and Rahman, 2003 who predicted thermal conductivity of food based on the control of moisture content, temperature, and apparent porosity. Zhu et al. (2007) use FL to predict combustion efficiency in a boiler, regulating the dosage quantity, percentage of mixture and moisture of poultry litter, excess air, and secondary air during combustion. In other words, FL is useful for decision-making where there are a variety of operating alternatives and therefore multiple potential results, so the return on technology investments is maximized (Zhang, 2012). FL is also useful for determining capital costs when there are uncertainty and risk involved in the investment (Karanovic and Gjosevska, 2012).

This entire analysis is developed on Monte Carlo simulation, in order to represent the inherent variability and uncertainty of the system into the model. This makes it possible to propagate variability and uncertainty into the results (Geisler et al., 2005), and therefore having a wide picture of the system when making decisions. According to Bieda (2014), studies based on Monte Carlo Simulation result in more flexible models since variables can be described by probability distributions, a better understanding of the behavior of specific outputs, and a better capacity to identify the most representative variables of the model.

This research proposes a methodology that includes seven stages to analyze the economic feasibility of generating bioenergy from the use of poultry litter during combustion, and consequently maximize the production of steam and electrical energy. The proposed methodology (section 2) analyzes the chicken production system to achieve moisture control in poultry litter, as well as to estimate the energy produced from CV to determine the energy, economic, and environmental potentials based on different moisture scenarios (25%, 30%, 35% and 40%). This methodology is validated through a case study in production farms of a Mexican poultry company (section 3), the results of which are shown in section 4.

2. Methodology

The methodology of this research includes: 1) analysis of the production system, 2) biomass quality control (poultry litter moisture), 3) estimates of the amount of poultry litter at different moisture contents, 4) balance of matter and energy (combustion) 5) determination of bioenergy production (thermal and electrical), 6) risk analysis with different scenarios to estimate economic profitability, and 7) evaluation of environmental sustainability (see Fig. 1).