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Environmental Efficiency of Pig Production in Chuong My District, Hanoi

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Abstract

Chuong My is a suburban district of Hanoi with a rapid development of pig farming, accompanied by the problem of environmental pollution. For the sustainable development of livestock production, besides improving production efficiency, it is necessary to reduce environmental pollution. This study measured production efficiency considering environmental factors (environmental efficiency) to assess the sustainability of pig farms in the district. This study used the data envelopment analysis (DEA) model with undesirable output (COD emissions) to measure environmental efficiency in pig production. The research results showed that the average production inefficiency score was 1.07, while the average environmental inefficiency score was 1.19. This shows that if environmental factors are not considered, the measurements of production efficiency are biased. Using Tobit regression, the study showed that the factors that increased environmental efficiency were the installation of biogas digesters and the pollutant removal efficiency of manure treatment facilities. Meanwhile, increases in the volume of wastewater discharging into the treatment plants reduced environmental efficiency. These findings confirm the importance of biogas plants in manure treatment in Vietnam. To improve environmental efficiency, it is necessary to enhance the efficiency of treatment facilities and apply water-saving technologies in livestock production.

Keywords

Data envelopment analysis, pig production, Tobit, undesirable output

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Introduction

Pig production in developing countries like Vietnam has played an important role in the agricultural sector, and has helped to alleviate poverty and improve people's livelihoods (Van Hung *et al.*, 2015). To meet the increasing demand for pork for consumption, pig farming is developing very rapidly, accompanied by a huge amount of waste. Because of inefficient waste management, pig production has faced serious environmental pollution problems (Huong *et al.*, 2014; Ho *et al.*, 2016; Huong *et al.*, 2019; Huong *et al.*, 2020a). In addition, due to outdated livestock facilities, expensive feed costs, a weak production management capacity, low market accessibility, and lack of linkages in production and consumption, the efficiency of pig production in Vietnam is low compared to other countries in the region and around the world (Jabbar & Akter, 2008; Ly *et al.*, 2016; Tung, 2016; Ly *et al.*, 2020). Therefore, pig production in Vietnam is not sustainable in terms of both production and the environment.

Production efficiency is defined as the conditions under which goods are produced at the lowest possible unit cost (Färe *et al.*, 2013). Technical efficiency (TE) measures the ability of a decision-making unit (DMU) to produce maximum outputs from a given set of inputs, or to minimize the use of inputs while still producing the current outputs. Production efficiency requires technical efficiency (Färe *et al.* , 2013). Regarding production aspects, previous studies have reported various technical efficiency values of pig production in Vietnam as being 65.7% (Huong *et al.*, 2023), 80.4% (Ly *et al.* , 2016), and 73% (Jabbar & Akter, 2008). Ly *et al.* (2016) indicated that the determinants of efficiency included average live weight, breeding time, experience, education level, number of family members involved in pig production, income from pigs, accessibility to credit, and veterinary services. Huong *et al.* (2023) argued that feed types, land formation, herd size, education, family size, duration of the fattening phase, floor space per pig, family income, and the proportion of piglets bred on the farms were the determinants. Jabbar & Akter (2008) showed that there were significant differences in technical efficiencies among pig farms in the North and South of Vietnam. The research showed that better output market access, increased land size, a larger herd size, and a higher education level of the household heads helped to increase the efficiency, while limited accessibility to inputs supplied by the government, older heads of household, female heads of household, and the use of homemade food reduced the efficiency. In general, market-related factors have a more consistent influence on technical efficiency of pig farms in the South, which has a longer market economy experience than in the North.

Production efficiency studies of pig production in Vietnam use normal inputs such as feed, breed, labor, depreciation, and other recurrent costs, as well as conventional outputs such as total liveweight of slaughtered pigs. Evaluating production efficiency in such a way could ignore the environmental pollution produced by pig production. Since pig production inevitably comes with undesirable outputs (e.g. wastewater and emissions), the measurement of pig farm performance must consider such undesirable factors. Faere *et al.* (1989) and Seiford & Zhu (2002) showed that the inclusion of undesirable outputs in the production efficiency measurement model would lead to different performance scores and rankings across farms/firms. In other words, a model that does not consider undesirable outputs cannot demonstrate the true relative efficiency of farms/firms.

Hanoi is one of the provinces with the largest number of pigs in the country with 1,097,094 heads as of 2020. Pig production plays an important role in improving livelihoods and family incomes. However, with the rapid development of pig production, environmental pollution has also become a serious problem for the city. Therefore, improving production efficiency together with reducing environmental pollution will play a very important role in the sustainable development of pig production in Hanoi. To simultaneously improve production efficiency and reduce emissions to the environment, scholars introduced the term environmental efficiency (EE) (Faere *et al.* , 1989; Reinhard *et al.*, 2000). EE is an economic approach that calculates the possibility of increasing undesirable inputs or decreasing undesirable outputs (emissions) while maintaining or increasing the good outputs (Faere *et al.* , 1989; Reinhard *et al.* , 2000); so EE is TE with undesirable outputs.

Lansink & Reinhard (2004) investigated the EE of pig farms in the Netherlands. The undesirable outputs were the P-surplus and NH_3

emissions. The study found that the EE was 86%, meaning that pig farms could reduce emissions by 14% while still maintaining outputs. New feeding techniques and genetic varieties reduced the P-surplus by 30% and NH_3 emissions by 20%. Modern housing techniques also helped reduce NH_3 emissions by 30%. Asmild & Hougaard (2006) analyzed the EE and production efficiency of pig farms in Denmark. The results of the study indicated that about half of the farms were inefficient, with average production inefficiencies of 11–17%. Even when production efficiency was achieved, there was still the potential for a 30% improvement in EE for 17% to 32% of the farms. When measuring EE, the research results indicated that half of the farms were inefficient with average efficiency scores ranging from 34% to 56%. Yang (2009) measured production efficiency, EE, and factors affecting these types of efficiencies of pig farms in Taiwan. The results showed that environmental efficiency was much lower than production efficiency, suggesting that farms had little incentive for taking wastewater treatment seriously. In addition, the study also showed that advanced wastewater treatment systems and farm heads with high technical qualifications due to participating in training programs on wastewater treatment were two decisive factors to improve EE. Previous studies have provided a lot of valuable information on EE in pig production, but some research gaps still remain. First, these studies were conducted in developed countries such as Denmark, the Netherlands, and Taiwan, while there have been no related studies in developing countries such as Vietnam. Second, most of these studies did not analyze the influence of the waste treatment system characteristics on EE.

To fill these research gaps, this study measured the EE of pig farms in Hanoi by unifying the production and environmental factors in the same efficiency measurement model. In addition, we compared the production efficiency with and without environmental factors. Moreover, we analyzed the factors affecting the EE to propose solutions to improve the EE. To the best of our knowledge, this is the first study to use the data envelopment analysis (DEA) model with undesirable outputs to analyze environmental efficiency in pig production in Vietnam.

Methodology

Sampling

Chuong My is a suburban district of Hanoi, with very developed livestock farming (Huong *et al.*, 2023). According to statistics from the Hanoi Statistics Office, by 2020, out of a total of 1741 livestock farms in Hanoi, the district had 564 livestock farms, accounting for 32.4%. For pig production, this is also one of the districts with the largest number of pig heads, 165,782 heads in 2020, accounting for more than 15% of the city's pig population (Hanoi Statistics Office, 2020).

Primary data were collected through interviews with pig farm heads in the district using questionnaires. In analyzing the environmental factors, we collected samples of wastewater discharged from the waste treatment plants of pig farms and analyzed them in the laboratory of the Faculty of Natural Resources and Environment, Vietnam National University of Agriculture. We chose chemical oxygen demand (COD) as the environmental factor to be analyzed in the EE model. We collected data from pig farms in three communes of the district, namely Lam Dien, Trung Hoa, and Dong Lac in March 2023. These are communes with developed pig farming at different farming scales. Large-scale and contract farming farms are concentrated in Lam Dien commune, while small-scale farms are located in Trung Hoa and Dong Lac communes. Using the random sampling method, we collected information by questionnaire and analyzed wastewater samples from 58 pig farms in these three communes.

Data analysis

Data envelopment analysis with undesirable outputs

Data envelopment analysis (DEA) uses linear programming problems to evaluate the relative efficiencies and inefficiencies of peer decision-making units (DMUs) which produce multiple outputs by using multiple inputs. Once DEA identifies the efficient frontier, DEA improves the performance of inefficient DMUs by either increasing the current output levels or decreasing the current input levels (Färe *et al.* , 2013). However, both desirable (good) and undesirable (bad) output and input factors may be present. The undesirable pollutants should be reduced while desirable outputs should be increased (Seiford & Zhu, 2002). However, we know that decreases in outputs are not allowed and only inputs are allowed to decrease in the standard DEA model. Faere *et al.* (1989) and Seiford & Zhu (2002) introduced techniques that allow researchers to decrease undesirable outputs or increase undesirable inputs. In this study, we attempted to decrease an undesirable output (COD in pig wastewater), while maintaining the other output and inputs.

According to Färe & Grosskopf (2004), there are strong and weak disposabilities of undesirable outputs, which have important impacts on the DMUs' efficiencies. A strong disposability of undesirable outputs means that the undesirable outputs are freely disposable. A weak disposability refers to situations when a reduction in waste or emissions forces a lower production of desirable outputs or when reducing undesirable outputs may not be possible without assuming certain costs (Hua & Bian, 2007). COD in pig wastewater is considered an undesirable output with weak disposability because the Vietnamese government sets limits on the COD value (100 mg/l and 300 mg/l for drinking and non-drinking water recipients). In addition, in treating the nitrogen in wastewater, pig farms must install treatment plants.

Suppose we have n decision-making units, denoted by DMU_j (j=1,2,…,n). Each DMU consumes m inputs x_{ij}, (i=1,2,…,m) to produce s desirable outputs y_{rj}, (r=1,2,…,s) and emit k undesirable outputs b_{tj}, (t=1,2,…,k). According to Färe & Grosskopf (2004), when the undesirable outputs are weakly disposable, the production possibility set may be written as:

$$T^w = \left\{ (x, y, b) \middle| \begin{array}{c} \sum_{j=1}^{n} \eta_j\, x_j \leq x, \sum_{j=1}^{n} \eta_j y_j \geq \\ y, \sum_{j=1}^{n} \eta_j\, b_j = b, \eta_j \\ \geq 0, j = 1,2, \dots, n \end{array} \right\} \quad \text{(Eq. 1)}$$

Seiford & Zhu (2002) developed a method for dealing with desirable and undesirable factors in DEA. They introduced a linear transformation approach to treat undesirable factors and then incorporated transformed undesirable factors into standard DEA models. Seiford & Zhu (2002) suggested a linear monotone decreasing transformation, $b_j = -b_j + v \geq 0$, where v is a proper translation vector that makes $b_j > 0$. That is, each undesirable output is multiplied by (-1) in order to find a proper translation vector v to convert negative data to non-negative data. Based upon the above linear transformation, the standard BCC DEA model can be modified as the following linear program:

$$Max\ h \qquad \text{(Eq. 2)}$$

$$Subject\ to$$

$$\sum_{j=1}^{n} \eta_j x_{ij} + s_i^- = x_{i0}, i = 1,2, \dots, m$$

$$\sum_{j=1}^{n} \eta_j y_{rj} - s_r^+ = h y_{r0}, r = 1,2, \dots, s$$

$$\sum_{j=1}^{n} \eta_j \bar{b}_{tj} - s_t^+ = h \bar{b}_{t0}, t = 1,2, \dots, k$$

$$\sum_{j=1}^{n} \eta_j = 1, \eta_j, s_i^-, s_r^+, s_t^+ \geq 0, for\ all\ i, j, r, t$$

The model implicates that a DMU can expand desirable outputs and decrease undesirable outputs simultaneously. A DMU is efficient if h=1 and all $s_i^- = s_r^+ = s_t^+ = 0$. If h>1 and (or) $s_i^-, s_r^+\ or\ s_t^+$ are non-zero, then the DMU is inefficient.

Since this study was interested in measuring the ability to reduce environmental pollution while keeping other factors constant, we used the concept of non-discretionary outputs (Banker & Morey, 1986). Non-discretionary outputs are those that are fixed in the DEA, while discretionary (undesirable) outputs are contracted. The DEA with undesirable output and non-discretionary output can be produced by R with the "deaR package" (Coll-Serrano *et al.*, 2023).

The normal inputs, non-discretionary output, and undesirable output of the DEA model are explained in **Table 1**. Normal inputs included feed cost, piglet cost, labor cost, depreciation, and other variable costs. They were the costs consumed to produce the total liveweight of slaughtered pigs in 2022. Labor costs included the rate for hiring laborers and the time family laborers spent on pig-raising activities converted into a monetary value. Depreciation included the depreciation of pigpens, waste treatment facilities, and other valuable assets. Other costs included electricity, water, vaccines, and medicines. The undesirable output was the total COD emissions from the total slaughtered pigs in 2022.

Tobit regression

After calculating the EE scores, the next step was to identify the determinants of the EE scores. Because EE is a continuous variable that varies between the interval of [1;∞], several regression models can be used such as the standard linear model (OLS) or Tobit model (Mcdonald, 2009). However, The OLS is not appropriate for such analysis because the predicted values of EE may lie outside the interval (Wooldridge, 2016), as EE scores produced by DEA are positive and equal to or more than one. The lower-limit Tobit model, the so-called censored regression model, can fix this problem (Wooldridge, 2016) because we can set the lower limit to 1, which ensures the predicted values of EE lie in the interval. The Tobit model for EE scores is expressed in Eq (3) as follows (Wooldridge, 2016):

$$h = ZB + e \qquad \text{(Eq. 3)}$$

$$h = \begin{cases} h^* \; if \; 0 < h^* < 1 \\ 0 \; if \; h^* < 0 \\ 1 \; if \; h^* > 1 \end{cases},$$

where Z is the vector of the independent variables including waste treatment plants, manure separation, ratio of manure to water entering to waste treatment plants, treatment area per pig, pond area, treatment efficiency of waste treatment plants, and wastewater volume per day (Park & Craggs, 2007; Vu *et al.*, 2010; Hong & Lieu, 2012; Thien Thu *et al.*, 2012; Huong *et al.*, 2014; Kashyap, 2017; Huong *et al.* , 2020a); h^* is the latent variable; h is the EE score; B is the estimated parameter; and e is the error term.

Statistical analysis

In this study, paired t-test was used to compare the production and environmental efficiency of pig farms.

Results and Discussion

Measurement of production and environmental efficiency

To measure technical efficiency in pig production, previous studies have used inputs such as feed, piglets, labor, depreciation, and other costs, with the output being the total liveweight of slaughtered pigs. A summary of the inputs and outputs is described in **Table 2**. The

Table 1. Introduction of inputs and outputs in DEA model

		Explanation	References
Inputs	Feed cost	Total feed cost to produce total liveweight in 2022 (VND)	Jabbar & Akter (2008); Lapar (2014); Ly *et al.* (2016); Ly *et al.* (2020)
	Piglet cost	Total cost of buying piglets/ self-producing piglets to the total liveweight in 2022 (VND)	
	Labor cost	Total labor cost, converted from pig raising work with rural labor rate (150,000 VND/day)	
	Depreciation	Depreciation of pigpens and fixed assets (VND)	
	Other variable costs	Cost of electricity, water, vaccines, medicines, etc. (VND)	
Desirable output	Total liveweight	Total liveweight in 2022	Jabbar & Akter (2008); Ly *et al.* (2020)
Undesirable output	COD	COD (kg) in wastewater emitted from manure treatment plants in 2022	Van Meensel *et al.* (2010); Huong *et al.* (2020a)

Table 2. Summary of inputs and outputs of the DEA model

Variable	Mean	Std. Dev.	Min	Max
Inputs				
Feed (USD)	124,689.80	128,504.40	511.36	550,227.30
Piglets (USD)	37,526.12	39,449.05	409.09	143,182.50
Labor (USD)	2970.51	3256.11	98.40	14,727.30
Depreciation (USD)	6048.82	8140.31	45.45	49,818.18
Other variable cost (USD)	12,864.93	12,920.04	36.36	44,454.54
Outputs				
Total liveweight of pigs (kg)	135,558.10	139,557.40	1800.00	585,000.00
COD emitted (kg)	636.36	758.70	3.14	3092.61

cost of animal feed accounted for the highest proportion (67.72%) of the total production cost. Lapar (2014) indicated that in recent years, the price of industrial feed in Vietnam has increased due to increases in the import prices of the main feed ingredients, and a significant proportion (20-30%) of feed ingredients are imported from other countries. More and more foreign and domestic companies are entering Vietnam to capture the high potential profits that can be generated from the production and sale of animal feed. In addition, multinational feed companies such as Cargill, C.P., and Japfa have established feed production facilities in Vietnam due to government reform policies as well as domestic and foreign investment incentives for investors in the feed industry. Farmers reported feeding pigs industrial feed or combined feed, which is a mixture of industrial feed and agricultural by-products. The use of combined feed has helped reduce feed costs and improve technical efficiency (Huong *et al.* , 2023). The piglet cost accounted for about 20% of the total production cost, being second only to the feed cost. Pigholders can buy piglets from hatcheries or breed them from their sows, which is said to save on piglet costs.

To measure environmental efficiency, previous studies have used normal and undesirable outputs. Undesirable outputs are usually pollutants emitted from production. According to the Vietnam National Technical Regulation on the Effluent of Livestock, regulated pollution factors include pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and total coliform (Ministry of Natural Resource and Environment, 2016).

We chose COD as the undesirable output because it is one of the main pollution indices in wastewater. Too high a COD index in wastewater reduces the quality of the water source by creating a stench, resulting in uncomfortable feelings for people around the water source. Aquatic organisms in recipient rivers cannot grow and reproduce and can even die in mass. In addition, toxins can gradually seep into other bodies of water and the soil, which affect production activities and human health such as causing dermatological problems and digestive diseases. The amount of COD emitted into the environment depends significantly on the pollutant removal efficiency of the waste treatment plants (Dinh *et al.*, 2020).

Production efficiency and environmental efficiency are described in **Table 3**. Production efficiency was calculated using an output-oriented DEA model, whereby the model measured the ability to increase the total liveweight of pigs with the observed inputs. Environmental efficiency was also calculated using an output-oriented DEA model with the nondiscretionary output as the total liveweight of pigs and the undesirable output as the COD emissions in wastewater. This means that for the observed inputs and total liveweight of pigs, the DEA model measured the ability to reduce COD emissions. With both models, when the score was 1, the farm was efficient, and when the score was greater than 1, then the farm was not efficient. The higher the score, the more ineffective the farm was. The mean production efficiency score was 1.07 while the mean environmental efficiency score was 1.72. This difference was determined by pair t-test to be statistically significant. This shows that if environmental factors are not considered in the DEA model, production efficiency can be biased. Some farms have made significant investments in waste treatment plants that caused depreciation costs to increase while output remained constant, which reduced production efficiency. But when the environmental factors were also taken into account, i.e. taking into account undesirable outputs, the efficiency was reduced. Yang (2009) measured productive efficiency and environmental efficiency in farrow-to-finish pig production in Taiwan. The results showed that production efficiency was higher than environmental efficiency, and they did not have the same distribution. The author concluded that using an identical ‘technical efficiency’ index to represent production and environmental efficiency would get a biased result when undesirable outputs were considered.

Determinants of environmental efficiency

Table 4 describes the variables used in the Tobit model to analyze the factors affecting environmental efficiency. All the farms applied a certain method of waste treatment such as slurry ponds and/or biogas digesters. About 84% of the surveyed farms had installed biogas digesters. Besides treating manure with biogas digesters and slurry ponds, farmers also separated manure to fertilize plants or pour into fishponds (Thien Thu *et al.*, 2012; Roubík *et al.*, 2016). Only about 17% of the farms separated manure while the majority discharged manure and washing water directly into biogas digesters. The ratio of manure to water was calculated by taking the amount of manure per day divided by the total amount of washing water discharged into the waste treatment facilities. The ratio of manure to water in the farms was high at 1 part manure to 20 parts water. According to Thien Thu *et al.* (2012), the use of too much water in washing the barns limits the removal of pollutants because the retention time in the biogas digesters is reduced. Slurry ponds or biological ponds were also parts of the manure treatment plants. The average pond area in the surveyed farms was about 2000m^2, of which there were farms with very large ponds of 30,000m^2. These types of ponds are believed to help reduce the amount of COD in the wastewater (Dinh *et al.*, 2020). The treatment efficiency of manure treatment plants plays an important role in minimizing environmental pollution (Thien Thu *et al.*, 2012; Roubík *et al.*, 2018). The COD treatment efficiency was calculated by subtracting the output COD concentration from the input COD concentration and then dividing the value by the input COD concentration. The average manure treatment efficiency of the surveyed farms was 29.57%, but there were farms with treatment efficiencies of 0. The volume of slurry discharged into the

Table 3. Production efficiency and environmental efficiency

Inefficiency Score	Production efficiency		Environmental efficiency	
	N	%	N	%
h = 1	20	34.48	29	50
1<*h*≤2	38	65.52	26	44.83
2<*h*≤3	0	0	2	3.45
h>3	0	0	1	1.72
Mean[(a)]	1.07		1.19	
SD	0.09		0.56	
Min	1.00		1.00	
Max	1.40		4.71	

Note: Paired t-test was conducted with t = -1.5828 at Pr (T < t) = 0.0595.

Table 4. Summary of variables used in the Tobit regression

Variable	Mean/case	Std. Dev.	Min	Max
Biogas (dummy)	49		0	1
Manure separation (Yes)	10		1	1
Ratio of manure to water	0.04	0.04	0.01	0.23
Pond area (1000m^2)	2.21	4.91	0.00	30.00
Treatment efficiency of the waste treatment plant (%)	29.57	30.93	0.00	92.32
Log of wastewater volume/day	3.33	1.22	0.18	5.19

treatment plants every day also greatly affects the environment. When the volume is too large, it leads to overload, shortens the retention time, and reduces the treatment efficiency (Thien Thu *et al.*, 2012; Roubík *et al.*, 2016). To avoid multicollinearity, we used the log of the volume of wastewater per day. With the mean of variance inflation index being 1.32 (**Table 5**), there was not multicollinearity in the Tobit model.

The results of the regression of factors affecting environmental performance are presented in **Table 6**. The results show that installing biogas plants helped to improve environmental efficiency. Biogas technology is a popular solution in Vietnam, creating multi-benefit values by not only reducing greenhouse gas (GHG) emissions and treating environmental pollution, but also by generating biogas (Thien Thu *et al.* , 2012; Roubík *et al.* , 2016; Roubík *et al.* , 2018). Biogas can be used as a fuel to replace traditional fossil fuels (coal, firewood, rice straw, etc.) or to produce electricity, bringing economic benefits and contributing to improving environmental quality and people's health. Biogas systems help to reduce odors and improve the landscape, creating a green and clean environment for livestock households because waste is concentrated and loaded into the biogas tank. The anaerobic decomposition process helps to destroy worm eggs, worms, pathogens, and stench from being spread around. Moreover, the anaerobic digestion technique in biogas tanks shows that the wastewater treatment efficiency is better than other traditional methods because the organic matter is partially decomposed, so the wastewater from biogas digesters has a low organic matter content and less odor, and the COD index can be reduced from over 4,000 mg/L to about 1,000 mg/L (Huong N.T.Q., 2018). Biogas tanks also help to reduce the direct discharge of waste into the environment, thereby reducing surface and groundwater pollution. However, Huong *et al.* (2014) indicated that biogas wastewater represents a potential hazard to human and animal health when released into the environment because *E. coli* is reduced by only 1 to 2 log units in biogas systems. Roubík *et al.* (2016) also pointed out some problems in operating biogas plants. The most common problem is related to leaks from the digesters that lead to undesirable CH_4 emissions, sometimes causing the biogas plants to shut down. Other problems are related to the biogas digesters not working properly with decomposing solid residue floating in the main tank, resulting in reduced biogas production. Another problem with biogas plants is excessive methane, especially at large-scale livestock farms. To avoid exploding or cracking the biogas digesters, it is necessary to release the gas, which increases the amount of greenhouse gasses (Thien Thu *et al.* , 2012). Therefore, it is necessary for further research on solving the problems associated with biogas technology. According to Ha T.T.T. *et al.* (2016), the treatment efficiency of biogas digesters also depends on a number of other important factors related to the knowledge, attitudes, and behaviors of users, the quality of the works, and the suitability of the volume of the biogas digesters with the livestock scale.

The higher the pollutant removal efficiency of manure treatment plants, the more they help to improve environmental efficiency. Research by Hong & Lieu (2012) indicated that biogas plants

Table 5. Variance Inflation Factor (VIF)

Variable	VIF	1/VIF
Biogas (dummy)	1.46	0.68
Manure separation (Yes)	1.14	0.88
Ratio of manure to water	1.27	0.79
Pond area (1000 m^2)	1.26	0.79
Treatment efficiency of waste treatment plant (%)	1.41	0.71
Log of wastewater volume/day	1.35	0.74
Mean VIF	1.32	

Table 6. Determinants of environmental efficiency

Variables	Coefficients	Standard Errors
Biogas (dummy)	-0.63*	0.32
Manure separation (Yes)	-0.13	0.32
Ratio of manure to water	2.19	3.92
Pond area (1000 m^2)	-0.02	0.02
Treatment efficiency of waste treatment plant (%)	-0.01**	0.00
Log of wastewater volume/day	0.19*	0.11
Constants	0.99*	0.54
Number of observations	58	
LR chi2(6)	19.54	
Prob > chi2	0.0033	
Pseudo R2	0.1785	
Log likelihood	-44.97	

*Note: ** P <0.05; * P <0.1.*

can remove 84.7% of the COD concentration in wastewater. However, the concentration of pollutants in the output wastewater was still quite high, exceeding the allowable standards. According to the research by Huong *et al.* (2021), manure treatment plants in pig farms can only reduce COD concentrations by about 29%. The main factors affecting the pollutant removal of biogas digesters are the anaerobic environment, temperature, retention time, and fermentation (Thien Thu *et al.* , 2012; Roubík *et al.* , 2016). Different types of waste treatment facilities lead to different pollutant treatment efficiencies. Huong *et al.* (2021) pointed out that combining biogas digesters and bio-ponds helps to improve the efficiency.

An increased amount of wastewater per day can also reduce the environmental efficiency. Each manure treatment facility has a certain treatment capacity. When the amount of wastewater exceeds the capacity, the treatment efficiency reduces. According to Ha T.T.T. *et al.* (2016), many households have more than 50 pigs, but their biogas digester volume is only 9-12m^3. With the standard of 2-3 pigs/m^3 of the biogas digester, these biogas plants are not capable of treating waste as regulated by standards. The volume of waste exceeds the design capacity of the treatment plants because the farms increase their livestock size after installing the waste treatment plants. Besides, many farms install manure treatment plants just to cope with environmental management agencies. Therefore, they only install small treatment plants to save money, not for treating waste. Another reason for the excess is the use of too much water for washing the pigpens. Farmers flush the slurry into the bio-digesters and stop adding water when the pigpens are clean (Thien Thu *et al.* , 2012). Vietnam is a tropical country with high humidity and temperatures, so farmers use a lot of water to wash and cool the barns. The amount of water then flows into the waste treatment system causing an overload (Huong *et al.*, 2020b). In reducing wastewater volume, Liang *et al.* (2017) suggested that part of the floor should be slatted. Then, below it, an automated scraper system can separate and collect the manure for later use. Urine and water can be collected and drained into a pre-treatment tank using a collection device, before entering the post-treatment facilities. This design would reduce daily water use from 50 liters/head to 7.5 liters/head.

Limitations of the study. Although this was the first study to use undesirable environmental factors in the analysis of the production efficiency of pig farms in Vietnam, it still had some limitations. Firstly, the sample size was small, resulting in low representativeness. Second, there are more important pollutants in pig wastewater that needed to be considered than just COD. These limitations suggest the need for further studies to expand the survey sample and the need to add more environmental indicators to the DEA model to measure environmental efficiency in pig production.

Conclusions

The results of the study have led to proposed solutions to improve environmental efficiency in pig production. The results showed that if undesirable environmental factors are ignored, the production efficiency measurement is biased. The research also showed that installing biogas digesters and improving the treatment efficiency of the manure treatment plants helped to improve environmental efficiency. Meanwhile, increases in the amount of wastewater discharged into the treatment plants reduced the environmental efficiency. With these findings, the study confirmed the importance of biogas plants in manure treatment in Vietnam.

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