Development of Manure Management Models

Sefa Aksu

Department of Agricultural Structures and Irrigation, Çanakkale Onsekiz Mart University, Çanakkale, Türkiye

e-mail: aksusefa@comu.edu.tr

***Abstract*—Animal production activities that begin with the domestication of animals are developing in line with the nutritional needs of the growing population. One of the inevitable consequences of this situation is increasing manure production. As a result of the increased use of mineral fertilizers in crop production, manure has begun to be seen as a problem to be disposed of for producers. The manure discharged into pastures and water resources has created a risk of pollution for production sites and natural resources eventually. As a result of the pollution that hinders the sustainability of production, it has become compulsory to create new areas of use for the evaluation of the environment. The use of nutrients as a source and soil conditioner in crop production is an effective method for evaluating manure. However, this method necessitates the storage of manure. According to physical conditions, the nutrients in the compost that cannot be stored or stored under unsuitable conditions have decreased nutrient amount and the production of pathogens has been observed. The fact that manure produces flammable gases as a result of microorganism activities indicates that it can be used as an energy source. It must be transported to meet the amount of manure required for energy production. The resulting transportation costs and operating costs of the facilities require economic planning. These results suggest that a manure management model should be used. The generated manure management model: to be sustainable, not to harm natural resources, to be economically viable, and to not affect the comfort of living in residential areas. The model needs to be specific to the region in order to achieve the desired conditions. In the study, the applications of manure management models designed according to daily development process and different needs are discussed.**

Keywords: Manure, Compost, Biogas, Manure management planning, Geographic Information System (GIS)

I. INTRODUCTION

Research on animal manure application at the farm scale initially relied on empirical-based approaches, in which nutrient supply estimations were conducted through programs assigning weighting coefficients to multiple influencing factors (Table 1). These approaches were primarily designed to optimize nutrient management at the individual farm level, and they focused on balancing the supply of essential nutrients with the specific demands of different crops. The fundamental parameters considered in such models were crop nutrient requirements, the amount of available nutrients present in the soil, and the nutrient composition and variability of animal manure. In addition to these agronomic aspects, several early programs introduced regulatory and environmental protection constraints, reflecting the growing awareness of issues such as nutrient leaching, surface water pollution, and greenhouse gas emissions associated with improper manure management.

Although these empirical programs provided practical tools for farmers, their reliance on simplified assumptions and their restriction to the farm scale significantly limited their broader applicability. Therefore, they did not adequately address the complexity of nutrient dynamics across landscapes, nor did they provide sufficient guidance for regional and national-level agricultural and environmental planning efforts. In many cases, their outputs were unable to support policy development, long-term sustainability goals, or large-scale nutrient recycling strategies.

During the same period, the widespread adoption and technological advancement of Geographic Information Systems (GIS) offered new opportunities to overcome these limitations. GIS provided a robust framework for integrating spatially explicit data on soils, crops, livestock, and manure resources over extensive areas, thereby facilitating more comprehensive and regionally relevant planning processes. The use of GIS not only increased the scale of analysis but also improved the precision of nutrient management recommendations by incorporating variations in landscape characteristics, soil fertility, and land-use patterns. Furthermore, the powerful visualization and modeling capabilities of GIS made it possible to simulate, test, and validate multiple management scenarios, allowing researchers and policymakers to evaluate potential outcomes before implementation. This integration of empirical knowledge with spatial technologies represented a significant step forward in developing manure management strategies that are both agronomically efficient and environmentally sustainable.

Table1. Some Empirical Based Approaches for Assigning Manure Application Rate

Program	Developer / Institution	Source	Scope
MAP	University of Minnesota	[1]	Economic feasibility and compliance with environmental protection standards
MARC98	Manitoba Agriculture	[2]	Determination of manure application rates based on manure nutrient content and crop nutrient requirements
MCLONE3	University of Guelph	[3]	Development of fertilization recommendations considering cost, labor, odor, and environmental protection requirements
AMANURE	Purdue University	[4]	Estimation of plant-available nutrients in animal manure to generate application recommendations that meet crop nutrient demands

II. Fertilization Model Studies

One of the area-based animal manure application models is the GIS-based Weighted Linear Combination (WLC) approach developed by [5]. The primary objective of this study was to determine site-specific manure application rates for animal production enterprises within the Murray-Darling Basin (Australia), considering the region's sensitive environmental requirements, and to provide application recommendations for areas deemed risky for fertilization. To achieve this objective, the study initially created a Boolean layer for each influencing factor within a GIS framework to identify risk-prone areas [6]. Subsequently, a risk rating map for the remaining areas was produced [7-9].

For the risk rating map, eight relevant factors were selected according to the literature: land use, soil type, slope, distance to intensive livestock operations, roads, streams, and residential areas [9]. A fuzzy classification was applied using Linear Scaling Equations (1, 2) for these factors:

$$X_i = \left(\frac{R_i - R_{min}}{R_{max} - R_{min}}\right) \quad (1)$$

$$X_i = 1 - \left(\frac{R_i - R_{min}}{R_{max} - R_{min}}\right) \quad (2)$$

where X_i is the scaled value of cell i; R_i is the value of cell i; R_{max} and R_{min} are the maximum and minimum values, respectively.

After classification, the Objective-Oriented Comparison (OOC) method was applied to determine the weighting coefficients of the factors [9]. The weighted and linearly scaled factors were then integrated using the WLC model (Equation 3) to generate manure application maps:

$$S_i = \sum_{j=i}^{n} (f_{ji.}scale \times w_j) \quad (3)$$

where S_i is the suitability value for each cell; f_{ji}.scale represents the grid point value for the factor attribute scale; and w_j is the relative weighting coefficient for factor j.

Finally, error matrices were created using GIS to calculate the proportions of different error types in the generated maps. The results indicated an overall accuracy of 87.1%, with a Kappa index (K) score of 0.71. In this study, both continuous and discrete factors were utilized to create matrices based on mathematical models, after which the weighting coefficients were assigned. Comparative weighting coefficients calculated for each factor were also used to define limit thresholds, preventing statistically unacceptable values. The relatively low error rates observed suggest that the methodology is reliable and applicable in practice.

A similar study conducted by [10] aimed to determine the use areas of animal manure based on its nutrient content, ensuring that crop nutrient requirements were met while considering environmental protection constraints and manure transportation costs. The study area was selected as Louisiana, USA. Due to the lack of road connections for intensive livestock operations and for crop production areas, it was necessary to define feasible manure application boundaries according to transportation costs. The average distance from farms without road access to the nearest roadway was calculated as 6.6 km, and Inverse Distance Weighted (IDW) interpolation maps were developed for these connections, taking into account terrain slope trends [11,12] (Equation 4):

$$Z_0 = \frac{\sum_{i=1}^{s} Z_i \frac{1}{d_i^k}}{\sum_{i=1}^{s} \frac{1}{d_i^k}} \quad (4)$$

where Z_0 is the predicted value at location 0; Z_i is the known elevation at point i; d_i is the distance between points i and 0; s is the number of points used for prediction; and k is a customizable exponent.

Using the existing road network, feasible routes for transport vehicles were determined, and road costs were calculated using the Network Analyst extension in GIS. Source and potential target points were organized in an OD (Origin-Destination) matrix. The nutrient content of animal manure was compared with mineral fertilizer costs within the matrix. The results indicated that transporting manure to satisfy the nitrogen (N) requirement of crops is feasible within a 30 km radius, whereas the phosphorus (P_2O_5) and potassium (K_2O) requirements could be met within a 15 km radius. The use of IDW and Network Analyst tools in this study demonstrates their applicability for generating terrain slope and road network maps for future planning. These tools are particularly useful for evaluating one of the main constraints in manure application—transportation costs.

Reference [13] conducted a study highlighting factors limiting the use of manure on pastures. By running a series of sequential mathematical models, the study aimed to estimate the accumulation of heavy metals in manure-fertilized pastures and the potential transfer to consumers via grazing. The model consisted of software for executing the equations and a GIS module for visualizing the results. The equations employed primarily included accumulation (Equation 5), leaching (Equation 6), exposure (Equation 7), and risk characterization (Equation 8):

$$\frac{d(C_s)}{d_t} = R_i - R_l - R_p \quad (5)$$

$$R_i = \frac{1000.F}{(k_d.\rho.d_p)} \quad (6)$$

$$C_{ed} = (C_p.PIR.f + C_s.SIR + C_w.WIR).BTF \quad (7)$$

$$HQ_{ij} = \frac{DD_{ij}}{RfD_i} \quad (8)$$

where C_s is the soil heavy metal concentration; R_i is the metal input rate; R_l is the leaching rate; R_p is the uptake by plants; F is additional precipitation; k_d is the soil-liquid partition coefficient; ρ is soil bulk density; d_p is tillage depth; C_{ed} is the heavy metal content in animal feed; C_p is the plant heavy metal content; PIR is pasture ingestion rate; f is the fraction of pasture in feed; SIR and WIR are soil and water ingestion rates; BTF is the bio-transfer factor; HQ_{ij} is the hazard quotient; DD_{ij} is the daily dose; and RfD_i is the reference dose.

The generation of risk zone maps based on these equations is facilitated by the GIS module. The researchers emphasized that the model is suitable for areas with dairy cattle operations and should be used in conjunction with a manure management program, confirming its applicability to planned study areas.

Finally, [14] developed a Decision Support System (DSS) model considering all factors of manure application, supported by local authorities. The system integrates environmental regulations and associated data repositories. Relying on both self-reported data from livestock producers and continuously updated public databases, the system provides managers with guidance for manure use. Although the system, targeting the sustainable production of the highly intensive Lombardy region (Italy), has not yet produced a fully operational model, it represents a framework for adjusting nutrient budgets. Establishing a similar DSS in the planned study area is currently limited by administrative infrastructure; however, the study outcomes are expected to inform model development for future decision support applications.

III. Biogas and Compost Production Facility Location Modeling Studies

As livestock production intensity increases within agricultural enterprises, the volume of manure generated rises correspondingly, expanding the spatial domain in which this organic resource can be applied. One prominent utilization of this material is the capture and utilization of combustible gases (biogas) produced by microbial activity in manure storage facilities and composting piles; these gases can be harnessed for renewable energy generation. In addition to energy production, manure treatment facilities frequently yield stabilized, composted products—such as matured manure and humic substances—that can be returned to agricultural fields as soil amendments. However, the presence of veterinary pharmaceuticals (e.g., antibiotics) in animal manure and the potential contamination from pesticides used in crop production may inhibit anaerobic digestion processes or affect compost quality, thereby reducing system efficiency and potentially undermining the economic viability of such facilities. Therefore, the strategic siting of biogas and composting facilities is critical for both operational performance and environmental protection.

Geographic Information Systems (GIS) provide powerful tools for integrating and analyzing diverse spatial datasets, enabling researchers and planners to assess the full suite of factors that influence optimal facility siting. The capacity of GIS to relate land use, infrastructure, environmental constraints, and resource availability makes it particularly suitable for biogas facility location studies, which is why GIS-based approaches are prevalent in the literature. For example, [15] applied GIS methods to identify potential anaerobic digestion (AD) facility locations in Tompkins County, New York (USA), exemplifying the application of spatial multi-criteria analysis to this problem domain.

In the [15]'s study, the Analytic Hierarchy Process (AHP) was employed to derive weighting coefficients for the various siting criteria. The AHP-derived weights then integrated into a mathematical framework and visualized within a GIS environment to produce a comprehensive suitability model. The modeling procedure explicitly identified legal and environmentally protected zones as constraints, thereby ensuring that proposed sites complied with regulatory requirements. Constraints were expressed mathematically as follows (Equation 9):

$$C_i = \prod_{k=1}^{m} C_{i,k} \tag{9}$$

where C_i denotes the Boolean constraint value assigned to cell i; $C_{i,k}$ denotes the Boolean value of cell i under constraint k; and m is the total number of constraints considered. In practice, a cell receives a TRUE (1) value only if it satisfies all constraint conditions, and FALSE (0) if it violates any one of them.

For the areas that remain after excluding constrained zones, the study computed a composite factor representing the cumulative contribution of multiple siting criteria (Equation 10):

$$F_i = \sum_{j=1}^{n} F_{ij} \tag{10}$$

where F_i is the aggregated factor score for cell i; F_{ij} is the score of cell i with respect to factor j; and n is the number of factors included in the analysis. Typical factors included distance to feedstock sources, proximity to waste-processing industries, land cover, slope, proximity to transport networks, and distance to sensitive receptors, among others.

To reduce the influence of differing measurement units and to clarify distinctions among candidate cells, a normalization step was applied. The authors used the following distance-based normalization formula (Equation 11) to scale factor values to a common range:

$$F_{stdij} = \frac{F_{ij} - F_{ij,max}}{F_{ij,max}}(-1) \tag{11}$$

where F_{stdij} is the normalized distance for factor j at cell i; F_{ij} is the original distance or raw score for factor j at cell i; and $F_{ij,max}$ is the maximum observed distance or score for factor j. This transformation yields normalized values that facilitate comparison across factors and enhance the interpretability of the aggregated suitability index.

Recognizing that criteria do not contribute equally to site suitability, the normalized cell values were weighed using the AHP-derived coefficients to form the final composite factor score (Equation 12):

$$F_i = \sum_{j=1}^{n} w_j . F_{ij} \tag{12}$$

where w_j is the weighting coefficient for factor j ($0 \le w_j \le 1$). The weighted sum produces a single factor-driven score per cell that reflects both the relative importance of each criterion and the standardized performance of the cell with respect to that criterion.

The final suitability index for identifying optimal anaerobic digestion locations was calculated by combining the Boolean constraint mask and the weighted factor score, as shown in Equation 13:

$$SI_i = C_i . F_i \tag{13}$$

where SI_i is the suitability index for cell i; C_i is the Boolean constraint value for cell i; and F_i is the composite factor score. Cells that fall within constrained zones ($C_i = 0$) are automatically excluded, while cells with higher F_i values indicate greater suitability subject to constraint compliance.

Beyond the formal criteria included in the GIS model, practical siting considerations such as proximity to the electrical grid and the feasibility of interconnection should not be overlooked. Linking a biogas facility to transmission or distribution infrastructure may involve complex technical, legal, and economic negotiations; lacking convenient access to grid infrastructure can materially increase capital and operational expenditures and thus jeopardize project feasibility, even if other spatial criteria favor a given location.

When biogas production is organized at a supra-farm scale—i.e., through centralized or regional facilities rather than individual farm digesters—the relative importance of constraints and factors shifts. For centralized systems, production scale, aggregated feedstock availability, energy generation capacity, and market access for electricity or biomethane become principal determinants of site suitability. Reference [16] conducted a regional assessment for Hokkaido, Japan, to identify potential centralized biogas plant locations and to evaluate their economic potential. In that study, population centers associated with livestock production were treated as aggregated feedstock nodes, and the analysis prioritized energy yield and marketability over small-scale accessibility constraints. Environmental protection requirements and transportation costs were explicitly considered as influencing factors, and the Network Analyst extension of GIS was used to model logistics and feasible plant locations.

Yabe's economic assessment included capital and operational cost estimates calculated over a 15-year project life. Under the parameterization used in that study, total projected costs exceeded anticipated revenues, suggesting limited economic feasibility for some centralized configurations under prevailing conditions. Nonetheless, the author emphasized that policy instruments (such as feed-in tariffs, subsidies, or regulatory reforms) and improvements in technology or fuel markets could alter the economic balance and render certain sites viable. This conclusion underscores the sensitivity of siting outcomes to economic assumptions and policy contexts and highlights the importance of integrating technical, environmental, and socio-economic analyses when planning biogas and compost production facilities.

IV. Conclusion

The rapidly increasing scale of livestock production has made it imperative to develop new strategies and innovative approaches for the sustainable management of manure. At this point, the primary consideration has been the alignment between the nutrients already available in the soil and the specific nutritional requirements of the cultivated plants [17]. In this regard, it has been emphasized that manure should be applied in quantities that prevent the excessive accumulation of macro-nutrients in the soil, thereby minimizing environmental risks while ensuring agricultural productivity [13]. Furthermore, it has been reported that when crop production is monitored effectively and crop rotation practices are properly implemented, the use of animal manure does not necessarily result in pollution or ecological degradation [18]. Nevertheless, one of the main constraints of manure management is that the seasonal period during which manure can be applied to agricultural land is relatively short, which necessitates the storage of large quantities of manure. During storage in pits or when stockpiled in heaps, manure undergoes intensive microbial interaction and biochemical transformation processes [19]. Moreover, the presence of veterinary pharmaceuticals administered to animals, as well as bedding materials mixed with manure, has been shown to contribute to nutrient losses and, in some cases, to the proliferation of pathogens [20]. To mitigate these negative outcomes, composting has been widely adopted as a practical and sustainable treatment method. Composting refers to the process in which organic fractions within waste are decomposed by aerobic microorganisms, transforming them into stable organic matter and plant-available mineral nutrients that can be safely returned to the soil.

In addition to aerobic microorganisms, manure also contains anaerobic microbial populations. The metabolic activities of these microorganisms lead to the release of methane and other combustible gases into the environment [21]. The combustion of these gases, collectively referred to as biogas, has been recognized as a valuable method for generating renewable energy, particularly electricity, from animal waste [22]. Alongside energy recovery, the process yields humic acid and stabilized organic fertilizer as by-products, which further enhances the economic attractiveness and sustainability of the approach [23].

The environmentally sound utilization of livestock manure, without creating pollution or ecological burdens, requires the comprehensive evaluation of a wide range of interrelated factors. These factors must be analyzed in ways that account for their potential interactions and combined outcomes. In this respect, the use of Geographic Information Systems (GIS), which are capable of visualizing statistical models, plays a crucial role in rendering complex analytical results into tangible, spatially explicit outputs. GIS, by classifying data and storing it in multiple thematic layers, provides the technical capacity to retrieve and employ the precise datasets required for model construction and decision-making [24].

In order to achieve economic valorization of livestock manure, whether through its direct application in crop production, through energy generation by means of biogas production, or through the preparation of compost for soil improvement, detailed and systematic planning is essential. Such planning processes should be conceptualized as models that ensure continuity and adaptability over time. Although certain modifications to these models may arise in parallel with regional transformations, shifts in national policies, or changes in cultural practices, the fundamental methodological steps should remain constant. Accordingly, it is of critical importance that, during the formulation of models, the influencing factors—such as cost efficiency, labor requirements, odor control, environmental protection measures, and relevant legal frameworks—be carefully defined in accordance with the needs and limitations of the specific region under study. Furthermore, model parameters should be systematically structured so as to address and respond to these factors in a coherent and scientifically justified manner.

References

[1] Schmitt, M. A., Levins, R. A. and Richardson, D. W. 1997. Manure application planner (MAP): software for environmental and economical nutrient planning. Journal of Production Agriculture 10, 441–446.

[2] Tessier, S. 1999. MARC98: User Manual Version 1.01. Edited by Sylvio Tessier, Animal Industry Branch, Manitoba Agriculture, Manitoba, Canada.

[3] Ma, K. ve Ogilvie, J. R. 1998 MCLONE3: A Decision Support System for Management of Liquid Dairy and Swine Manure; 7th International Conference on Computers in Agriculture, October 26–30, Orlando, Florida, USA.

[4] Sutton, A. L., Jones, D. D., Joern, B. C. and Huber, D. M. 1994. Animal Manure as a Plant Nutrient Resource, ID-101, Cooperative Extension Service, Purdue University, West Lafayette, USA.

[5] Basnet B. B., Apan A. A., Raine S. R., 2002. Geographic Information Systems Based Manure Application Plan. Journal of Environmental Management. 64, 99-113.

[6] Basnet, B. B., Apan, A. A. and Raine, S. R. 2000. Selecting Site Suitable for Animal Waste Application using a Vector GIS. Conference on Engineering in Agriculture, SEAg 2000 Growing Links, 2–5 April, Adelaide, Australia.

[7] Siddiqui, M. Z., Everett, J. W. and Vieux, B. E. (1996). Landfill siting using geographic information systems: a demonstration. Journal of Environmental Engineering 122, 515–523.

[8] Eastman, J. R. 1999. IDRISI32: Guide to GIS and image processing. Worcester, USA: Clark Labs, Clark University.

[9] Basnet, B. B., Apan, A. A. and Raine, S. R. 2001. Selecting suitable sites for animal waste application using a raster GIS. Environmental Management 28, 519–31.

[10] Paudel K. P., Bhattarai K., Gauthier W. M., Hall L. M., 2009. Geographic Information Systems (GIS) Based Model of Dairy Manure transportation and Application with Environmental Quality Consideration. Waste Management. 29, 1634-1643.

[11] Burrough, P.A., McDonnell, R.A., 2000. Principles of Geographic Information Systems: Spatial Information Systems and Geostatistics. Oxford University Press.

[12] Chang, K., 2006. Introduction to Geographic Information Systems, third ed. McGraw Hill Higher Education.

[13] Rio M., Franco-Uria A., Abad E., Roca E., 2011. A Risk-Based Decision Tool for the Management of Organic Waste in Agriculture and Farming Activities (FARMERS). Journal of Hazardous Materials. Issue: 185. p. 792-800.

[14] Acutis,M., Lodovico A., Andrea G., Giorgio P., Andrea Di G., Stefania C., Gianpaolo B., M. C., Guido S, Maurizio M, Mattia S, Alessia P, Marco C, Marcello E. Chiodini, M. F., 2014. ValorE: An integrated and GIS-based decision support system for livestock manure management in the Lombardy region (northern Italy), Land Use Policy, 41, 149-162.

[15] Ma J., Scott N. R., DeGloria S. D., Lembo A. J., 2005. Siting Analysis of Farm-Based Centralized Anaerobic Digester Systems for Distributed Generation using GIS. Biomass and Bioenergy. 28, 591-600.

[16] Yabe N., 2013. Environmental and Economic Evaluations of Centralized Biogas Plants Running On Cow Manure İn Hokkaido, Japan. Biomass and Bioenergy. 49, 143-151.

[17] Miner J.R., Humenik F.J., Overcash M.R., 2000. Managing Livestock Wastes to Preserve Environmental Quality. Iowa State University Press, Ames, Iowa.

[18] Li W., Li Y.X ., Zhang X.L., Yang M., Liu B., Wang J., 2012. Farmland Loading Capacity for Animal Manure and its Application Strategy in the Municipality of Beijing, China. Fresenius Environmental Bulletin. Vol. 21. Issue: 2. p. 269-275.

[19] Zhu J., Ndegwa P.M., Zhang Z., 2004. Manure Sampling Procedures and Nutrient Estimation by the Hydrometer Method for Gestation Pigs. Bioresource Technology. 92. p. 243-250.

[20] Hansen, M., Krogh, K.A., Bjöklund, E., Brandt, A., Halling-Sorensen, B., 2009. Environmental risk assessment of ionophores. Trends Anal. Chem. 28, 534– 542.

[21] Maeng H, Lund H, Hvelplund F. 1999. Biogas plants in Denmark: technological and economic developments Appl Energy ;64:195–206.

[22] Deublein D, Steinhauser A. 2008. Biogas from waste and renewable resources an introduction. Weinsheim: Wiley-VCH.

[23] Yadvika S, Sreekrishnan TR, Kohli S, Rana V. 2004. Enhancement of biogas production from solid substrates using different techniquesea review. Bioresource Technology; 95(1):1e10.

[24] Chrisman N., 2002. Exploring Geographic Information Systems. Second Edition. John Wiley and Sons, Inc. p.16-18.