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Research Article

Cost-Effective Forage and Browse Legume Feed for Dairy Production: An Optimisation Approach Using Jaya Optimisation Algorithm

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Livestock feed mix or feed choice decision-making is encountered by farmers in their daily operations. Livestock feed choice and mixing is emerging as a key research area considering the impact of climate change and emergence of new technology. Smallholder dairy farmers are usually capital constrained and hence a need to investigate cost-effective feed choice that maximises profit. A study to investigate the cost-effective feed among forage and browse legumes was conducted among smallholder dairy farmers in Zimbabwe. An optimisation problem was formulated with the objective of maximising profit by selecting the most cost-effective feed among forage and browse legumes. Secondary data are used to solve the optimisation problem by implementing the Jaya optimisation algorithm. Results show that grain crop silage is the best feed choice resulting in a maximum profit of $ 66.00 per day per farmer. Further research can be directed towards investigating the effect of combining the next best feed, quality hay, and grain crop silage for profit contribution.

1. Introduction

Climate change has affected grazing lands thereby impacting dairy production to a greater extent. Erratic rainfall affects the growth of grass which is regarded as the conventional food source for dairy cattle by smallholder farmers in Zimbabwe. Dairy output has been greatly reduced over the years [1]. Low milk production has been attributed to forage quality and management [2]. A study by Chinogaramombe et al. [3] found that low milk production among smallholder farmers was mainly due to feed unavailability. These results are a clear indication that measures to supplement feed for dairy cattle are a necessity. Forage and browse legumes have some advantages, especially for smallholder farmers.

Forage and browse legumes have a low reliance on fertilizer such as nitrogen inputs which are usually expensive for smallholder farmers. In this study, the term forage and browse legumes is defined as those parts of plants that are edible including mast, herbage, and browse but exclude separated grains. Examples are *Mucuna pruriens* and *Lablab purpureus*. Forage and browse legumes provide feed for animals, and a farmer can harvest them. The advantage of forage is that it is associated with a high voluntary intake of feed and high protein content. Although there are several advantages of forage and browse legumes to smallholder farmers, their use is low [4]. There are some disadvantages that they are associated with forage and browse legumes. The main disadvantage of depending on forage and browse legumes as feed is that there is a lower persistence in the growth of these compared to the grass under grazing. Forage and browse legumes have a high risk of bloating in livestock in some cases and are highly sensitive to changes in some specific factors easily compared to grass. The advantages of forage and browse legumes outweigh their demerits. A study carried out by Mugisa et al. [5] revealed that farmers who can integrate legumes into their animal diet are likely to obtain more herbage that remains greener into the dry season.

Optimisation is one of the approaches that can be used to ensure cost-effective feeds are produced. Previous works which utilised optmisation techniques include animal diet

Table 1: Definition of parameters and variables.

Name	Definition	Description
α	Index identifying farmer	—
λ	Production year	—
γ_β	Cost for production of product β	Par
κ_β	Storage cost of product β	Par
τ_β	Transportation cost of product β	Par
η_β	Shortage cost of product β	Par
i	Index identifying feed	—
j	Index identifying labour	—
k	Index identifying veterinary requirement	—
l	Index identifying fixed factors	—
n	Index identifying inefficient factor	—
t	Index identifying time	—
$A_{\beta t}$	Production of product p at time t	
$B_{\beta t}$	Inventory of product β at time t	
$B'_{\beta t}$	Shortage of product β at time t	
$C_{\beta t}$	Market price of product β at time period t	Par
$C_{\alpha t}$	Marginal cost of transportation milk from farmer α at time t	Par
C_i	Cost of feed i	Par
C_j	Cost of labour j	Par
C_k	Cost of veterinary requirement k	Par
C_l	Cost of fixed factor l	Par
C_n	Cost of inefficiency n	Par
d_t	Number of days in time period t	Par
$E_{\beta pt}$	Quantity of product β produced by process p at time period t	Var
F_i	Feed type i	Var
G_j	Labour type j	Var
H_k	Veterinary requirement k	Var
M_l	Fixed factor l	Var
$Q_{\alpha t}$	Quantity of milk supplied by farmer α at time t	
$Q'_{\alpha t}$	Percent of milk supplied by farmer α at time t	
R'_{tp}	Milk processing capacity of process p at time t	
R_{tp}	Milk processed at time t by process p	
U_n	Inefficient move n	Var
$S_{\alpha t}$	Milk supply at time t from farmer α	
$X_{\alpha t}$	A constant of milk production at time t from farmer α	
$Y_{\alpha t}$	Milk supply growth at time t from farmer α	
$W_{\beta t}$	Quantity of sales of product β at time period t	
$W'_{\beta t}$	Quantity shortage of product β at time period t	
$\overline{W_{\beta t}}$	Market capacity of product β at time period t	

optimisation [6], feed mixing [7], livestock feed optimisation [8], optimising organic feed mix problem [9], and several others.

The Jaya optimisation algorithm has been developed by Venkata Rao [10]. The algorithm attempts to achieve victory by achieving accomplishments which are used for discovering an optimal solution. The Jaya optimisation algorithm has been applied to solve distribution systems [11], optimisation of thermal devices [12], solve linear power systems to an interconnection [13], and economic load dispatch optimisation problems [14]. The objective of this study is to find the feed among forage and browse legumes that gives the maximum profit to a smallholder dairy farmer. This study has been motivated by the study by Mapiye et al. [15] to determine the level of adoption of forage and browse legumes. The remainder of this paper is arranged as follows: development of the optimisation model is presented in Section 2, computation of the model and results are presented in Section 3, and finally, Section 4 presents conclusions.

2. Materials and Methods

2.1. Development of a Model. In this section, a feed mixing mathematical programming problem is developed. Firstly, model parameters are defined and thereafter formulation of the model is presented. Table 1 presents the definitions of parameters and variables that are used in the development of the model.

2.2. Objective Function. The objective is to maximise profit and farm household income from milk production and production variables such as feeds, labour, veterinary expenses, fixed factors, inefficiency measure, and

socioeconomic factors affecting inefficiency are included as decision variables. Equation (1) is the proposed objective function.

$$\begin{aligned}\text{Max } Z = &\sum_i C_i F_i + \sum_j C_j G_j + \sum_k C_k H_k + \sum_l C_l M_l - \sum_n C_n U_n \\ &+ \sum_\beta \sum_t \left[C_{\beta t}\left(W_{\beta t} + \widetilde{W_{\beta t}}\right) + \gamma_\beta A_{\beta t} + \kappa_\beta B_{\beta t} \right. \\ &\left. + \tau_\beta W_{\beta t} + \eta_\beta W'_{\beta t} + \eta_\beta B'_{\beta t} \right] \\ &+ \sum_\alpha \sum_t C_{\alpha t} Q_{\alpha t}.\end{aligned} \tag{1}$$

2.3. Milk Production. Equation (2) is a constraint stating milk production, a sum of forecast milk supply from each farmer. The processed milk at time t by process p and under the capacity of the process p is presented by equation (3). The balance of milk flow production is presented by equation (4) which is the total of milk supply and incoming milk which is less than or equal to outgoing and processed milk.

$$\sum_\alpha \sum_t X_{\alpha t} + \lambda \sum_\alpha \sum_t Y_{\alpha t} + = \sum_\alpha \sum_t S_{\alpha t}, \quad \forall t \in T, \forall \alpha, \tag{2}$$

$$\sum_p \sum_t R_{pt} \le \sum_p \sum_t R'_{pt}, \quad \forall t \in T, \forall p \in P, \tag{3}$$

$$\sum_\alpha \sum_t S_{\alpha t} + \sum_\alpha \sum_t Q'_{\alpha t} \le \sum_t \sum_p D_t R_{tp}, \quad \forall \alpha, \tag{4}$$

$$\sum_\alpha \sum_t Q_{\alpha t} \le \sum_\alpha \sum_t Q'_{\alpha t} S_{\alpha t}. \tag{5}$$

2.4. Production and Storage Constraints of Milk By-Products. Equation (6) is the total production of the product β at time period t, and equation (7) presents the product flow balance.

$$\sum_\beta \sum_t A_{\beta t} \le \sum_\beta \sum_p \sum_t D_t E_{\beta pt} \sum_p \sum_t R_{pt}, \quad \forall \beta, \tag{6}$$

$$\sum_\beta \sum_t B_{\beta t} + \sum_\beta \sum_t W_{\beta t} \le \sum_\beta \sum_t A_{\beta t} + \sum_\beta \sum_t B_{\beta t-1}. \tag{7}$$

2.5. Inventory and Market Constraints. The total inventory in the previous time period $t-1$ and products that were bought during the shortage have to meet the inventory at that time period. Equation (8) presents this argument. Market capacity cannot be exceeded by the total sales of the product β in the time period t, and this is presented by equation (9).

$$\sum_\beta \sum_t B_{\beta t} + \sum_\beta \sum_t B'_{\beta t} \ge \sum_\beta \sum_t B_{\beta t}, \tag{8}$$

$$\sum_\beta \sum_t W_{\beta t} + \sum_\beta \sum_t W'_{\beta t} \le \sum_\beta \sum_t \widetilde{W_{\beta t}}. \tag{9}$$

The mathematical programming problem for the dairy farm problem is presented as follows:

$$\begin{aligned}\text{Max} Z = &\sum_i C_i F_i + \sum_j C_j G_j + \sum_k C_k H_k + \sum_l C_l M_l \\ &- \sum_n C_n U_n + \sum_\beta \sum_t \left[C_{\beta t}\left(W_{\beta t} + \widetilde{W_{\beta t}}\right) \right. \\ &\left. + \gamma_\beta A_{\beta t} + \kappa_\beta B_{\beta t} + \tau_\beta W_{\beta t} + \eta_\beta W'_{\beta t} + \eta_\beta B'_{\beta t} \right] \\ &+ \sum_\alpha \sum_t C_{\alpha t} Q_{\alpha t}, \\ &\sum_\alpha \sum_t X_{\alpha t} + \lambda \sum_\alpha \sum_t Y_{\alpha t} + = \sum_\alpha \sum_t S_{\alpha t}, \quad \forall t \in T, \forall \alpha \\ &\sum_p \sum_t R_{pt} \le \sum_p \sum_t R'_{pt}, \quad \forall t \in T, \forall p \in P \\ &\sum_\alpha \sum_t S_{\alpha t} + \sum_\alpha \sum_t Q'_{\alpha t} \le \sum_t \sum_p D_t R_{tp}, \quad \forall \alpha \\ &\sum_\alpha \sum_t Q_{\alpha t} \le \sum_\alpha \sum_t Q'_{\alpha t} S_{\alpha t} \\ \text{Subject to} \quad &\sum_\beta \sum_t A_{\beta t} \le \sum_\beta \sum_p \sum_t D_t E_{\beta pt} \sum_p \sum_t R_{pt}, \quad \forall \beta \\ &\sum_\beta \sum_t B_{\beta t} + \sum_\beta \sum_t W_{\beta t} \le \sum_\beta \sum_t A_{\beta t} + \sum_\beta \sum_t B_{\beta t-1} \\ &\sum_\beta \sum_t B_{\beta t} + \sum_\beta \sum_t B'_{\beta t} \ge \sum_\beta \sum_t B_{\beta t} \\ &\sum_\beta \sum_t W_{\beta t} + \sum_\beta \sum_t W'_{\beta t} \le \sum_\beta \sum_t \widetilde{W_{\beta t}}.\end{aligned} \tag{10}$$

3. Results and Discussions

3.1. Data Generation. Secondary data gathered in 2015 from smallholder farmers in the Chikwaka communal area in Goromonzi district located approximately 51 km east of Harare, Zimbabwe, are used. The data were collected from a total of 60 smallholder dairy farmers. The farmers deliver their milk to the milk collection centre where it is processed and delivered to retailers as fresh milk or milk by-products. Summary of feed available, milk quantities information and costs are presented in Tables 2–4, respectively.

3.2. Implementation of the Model

3.2.1. Jaya Optimisation Algorithm. The Jaya optimisation algorithm which was introduced in [10] can be used to solve constraint and unconstrained problems implemented as follows:

(i) Initialising the population size in this study, this includes the number of smallholder dairy farmers, feed options variables resulting in a fitness function

(ii) Analyse the fitness function value for each candidate, evaluate possible options and related costs

(iii) Equate the fitness function to the population size

(iv) Select the finest candidate and the worst candidate from the population

Table 2: Summary of feed available.

Category of feed	Mean	Minimum	Maximum
Best-quality hay	43.50	0	79.50
Low-quality hay	14.50	0	76.40
Best-quality silage	247.60	143.6	311.3
Grain crop silage	243.80	241.1	250.2
High moisture grain	173.60	69.30	239.10
Dry grain	14.50	0	104.00
Forage	295.80	150.60	365.50

Table 3: Summary of costs.

Description	Cost (USD)
Milk cost/litre	$0.65
Feed costs (purchased plus home-grown)	$568.75
Veterinary costs (drug and vaccines)	$136.70
Labour costs (family and hire)	$337.50
Storage cost	$2.00/day
Shortage cost	$20.00/day
Inefficiency costs	$50.00/month
Transport costs	$51.19

Table 4: Summary of farmer capacity.

Description	Value
Average daily milk quantity/farmer	240 litres
Number of farmers	60
Milk processing capacity	1500 litres/day
Quantity of milk processed/day	935 litres
Monthly feed (kg)	2100
Quantity of sales/day	850 litres
Quantity of milk shortages	1000 litres

Table 5: Summary of results.

Variable	Value
Profit/day/farmer (USD)	$66.00
Milk inventory/day (litres)	535
Allowable milk shortage/day (litres)	100
Maximum of feed requirement/day/farmer of grain crop silage (kg)	225

(v) Select the fitness function value for the updated candidate

(vi) Accept the new solution if it is better than the old one.

Computational experiments were performed in MATLAB 7.0.4 on a PC with Intel(R) Core(TM) i7-8550U @1.99 GHz and 16.00 GB RAM. A total of 250 computational evaluations of possible solutions were conducted to get the best optimal solution. Results are presented in Table 5. Results show that a smallholder farmer will get a profit of US $66.00 after feeding cows with grain crop silage on any given day. This result is based on a daily supply of 240 litres of fresh milk to the milk collection centre by a smallholder farmer. It is also shown from optimisation results that the milk collection centre should have at least 535 litres of fresh milk inventory to reduce daily milk shortages resulting in 100 litres allowable shortage. Although there are costs associated with storing milk such as electricity or backup power source, the tradeoff of inventory is far much more beneficial compared to the associated costs. It is therefore encouraged that farmers supply their milk to the milk collection centre as opposed to selling locally at lower prices.

Table 6: Feed available options versus profit.

Category of feed	Maximum quantity/day (kg)	Profit (US$)
Best-quality hay	75.0	52.70
Low -quality hay	76.40	32.45
Best-quality silage	300.0	44.90
Grain crop silage	245.0	66.00
High moisture grain	239.0	47.33
Dry grain	103.00	48.00
Forage	364.0	25.35

Table 7: PCA for feed and associated costs reduction.

Variable	Allowable increase	Allowable decrease	Reduced cost (US$)
Best-quality hay	10.00	5.10	23.25
Low-quality hay	30.50	0.01	43.32
Best-quality silage	Infinity	0.56	67.53
Grain crop silage	Infinity	6.00	46.12
High moisture grain	17.00	0.22	21.01
Dry grain	74.00	48.00	23.23
Forage	Infinity	3.88	0.00

Results in Table 6 show that the grain crop silage feed is attributed to a larger proportion contribution of profit as presented earlier, and the result is similar to the finding of Flaten et al. [16]. Farmers will require 245 kg of grain crop silage per day to realise a profit of US $66.00. The second best feed is the best quality hay which gives a profit of US $52.70. This feed type is required in smaller quantities as compared to other feed types. Low-quality hay results in the least profit of US $32.45. Results show that forage and browse legumes produce the least profit of US $25.35 among all the feed types that were included in this research.

Sensitivity analysis of feed types and the resultant contributions were performed in GAMS following procedures outlined in the principal component analysis (PCA) procedure. A summary of PCA results is presented in Table 7. Results show that grain crop silage does not have any limit in allowable increase, and the allowable decrease quantity is 6 kg which would reduce costs by $46.12. Results show that there is no reduction in costs when the farmer use forage and browse legumes as feed. This may be caused by the reason that forage and browse legumes are required in large quantities requiring a considerable large labor force thereby increasing labor costs and this concurs with the study by Peyraud et al. [17] (see Table 7 for more information).

4. Conclusions

This work involved the formulation of a feed mixing optimisation problem that was solved by utilising the recently developed Jaya optimisation algorithm. The Jaya optimisation algorithm proves to be a useful tool in determining the optimal livestock feed among the cost-effective forage and browse legumes for dairy production. In this study, additional constraints which are usually excluded in previous feed mixing problems such as summation of costs of the ingredients and limitation on the amount required were included. Grain crop silage feed is attributed to the best profit realization by dairy smallholder farmers. Further studies may focus on determining the profit contribution of combining grain crop silage with high-quality hay since high-quality hay is required in small quantities.

Data Availability

Secondary data were used which can be accessed upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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