Development of a Multipurpose Feed Enzyme Analyzer to Estimate and Evaluate the Profitability of Using Feed Enzyme Preparations for Poultry

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ABSTRACT

Previous studies have demonstrated that a log-linear equation could accurately predict chick performance when a feed enzyme was added to a diet and that the slope of the equation provided a measure of the efficacy of different enzymes. The objective of the study was to develop a software package, a Multipurpose Feed Enzyme Analyzer (MPFEA), based on an equation designed to evaluate the profitability of using feed enzymes. A high correlation between the efficacy of different feed enzymes (B values, the slopes of the equations) and the maximal profits was obtained when feed enzymes were added to a barley-based diet ($r^2 = 0.99, P < 0.0005$). In contrast, there was a low correlation between the B values and the maximal profits when a feed enzyme was added to different cereal-based diets ($r^2 = 0.61, P = 0.2171$). It appeared that there is not always a close association between efficacy of an enzyme when added to different cereal-based diets and the corresponding profitability. The MPFEA was highly versatile, as any combination of inputs such as the amounts of a feed enzyme and a substituted cereal required to yield a profit level could be determined. In conclusion, the MPFEA can accurately evaluate profitability of using different feed enzymes; select the most profitable cereal for a given feed enzyme; determine the optimal amounts of a feed enzyme, a cereal, or both; and even estimate the alternate price for a feed enzyme and a cereal. It should provide a useful tool for nutritionists.

(Key words: feed enzyme, maximal profit, profit function, log-linear model)

INTRODUCTION

There has been increasing interest in quantitatively studying the effect of different levels of feed enzymes when added to a cereal-based diet, such as barley, wheat, triticale, rye, or corn, on the performance of chickens (Friesen et al., 1991; Bedford and Classen, 1992; Marquardt et al., 1994; Jeroch et al., 1995; Zhang et al., 1996, 2000b). The primary objectives of the former studies were to estimate the optimal level of feed enzyme addition required to obtain maximal chick performance (Friesen et al., 1991; Bedford and Classen, 1992) and to evaluate the efficacy of feed enzymes added to a diet (Rotter et al., 1989; Zhang et al., 1996, 2000b). Frequently, the experimental designs and statistical procedures used in dose-response studies, especially when two or three discrete doses are studied, have only provided general trends on the effects of enzyme treatment but have not provided accurate prediction values, which is especially true if prediction equations are not used or if they are improperly selected. Therefore, it has been impossible to accurately estimate the relationship between enzyme or cereal inputs on chick performance outputs or to establish the most profitable combination of inputs for a specified output.

In addition, researchers in nutrition have generally been concerned only with biological criteria rather than economic criteria to evaluate and make recommendations on the effects of feed enzymes. The criteria that have been used for the evaluation of performance often were the treatments yielding the largest weight gain or the lowest feed to gain ratio per unit of enzyme addition (Friesen et al., 1991; Bedford and Classen, 1992). However, these maxima or minima have seldom been utilized to estimate the optimal input or most profitable output. Even when the objective was to predict the physical maxima or minima, the exact values could only be estimated accurately by use of a prediction equation (Zhang et al., 1996, 2000b).

Recently, we have developed a simple log-linear model to accurately predict the response of chickens to dietary

Abbreviation Key: CC = Celluclast; CT = Cellulase Tv; MPFEA = Multipurpose Feed Enzyme Analyzer.
enzymes (Zhang et al., 1996). The log model transforms the data into straight lines resulting in two obvious advantages for feed enzyme researchers: 1) theoretically, the response data from two or three doses are enough to generate a straight line that provides a basis for accurate predictions and 2) the log-linear model is simple and its parameters provide useful biological values (Zhang et al., 1996, 2000b). In contrast, performance data obtained from most dose-response studies are normally depicted as being curvilinear (Friesen et al., 1991; Bedford and Classen, 1992) and, therefore, do not provide similar advantages. We have demonstrated that the model equation was able to accurately predict the performance of chickens fed diets containing different amounts of an enzyme and different proportions of two cereals. We also found that simple but accurate log-linear equations could be derived from many previous dose-response studies with feed enzymes, even though they were not designed for this purpose (Zhang et al., 1996, 2000b). In addition, the efficacy of any enzyme preparation for a particular cereal or class of poultry with regards to any index of animal performance, such as weight gain or feed to gain ratio, could be assessed from a single value of B, the slope of the log-linear model equation (Zhang et al., 1996, 2000b; Marquardt and Bedford, 1997). Therefore, it should be possible, using this equation along with other analyses, to correctly estimate the maximum economic return obtained when a feed enzyme is added to a diet. One requirement is that accurate input data be available.

The objective of this study was to develop a Multipurpose Feed Enzyme Analyzer (MPFEA) for estimating the profitability of using enzymes in poultry feeds. Three main applications of the enzyme analyzer were: 1) to evaluate the effects of different enzyme preparations when they are added to a cereal-based diet using maximal profit as a standard, 2) to determine the amount of an enzyme preparation, a substituted cereal, or both that should be used in a diet to obtain maximal profit, and 3) to establish the relationships among the price of an enzyme preparation, the price of the substituted cereal, and the economic return. Therefore, the use of the modeling method in conjunction with nutrition knowledge and computer technology should provide researchers and managers that use feed enzymes with a powerful new approach for analysis and interpretation of their data.

MATERIALS AND METHODS

Sources of Data

The data used in this study were obtained from four previous studies: Rotter et al. (1989), Bedford and Classen (1992), Marquardt et al. (1994), Zhang et al. (1996). The data for the first study were obtained from Rotter et al. (1989) and Zhang et al. (1996). In Experiment 3 of the study from Rotter et al. (1989), 1-d-old Single Comb White Leghorn chicks were fed a commercial starter crumble for a 7-d pre-experimental period. A barley-based diet was fed to birds from 7 to 14 d of age in a completely randomized design. The diet consisted of the following ingredients: 65.50% barley, 23.07% soybean meal, and 11.43% other ingredients. The calculated ME₀ of the diet was 2,917 kcal/kg. Five enzyme preparations used in the study were: Cellulase Tyconcentrate (Trichoderma viride), β-glucanase (Aspergillus niger), β-glucanase (Trichoderma viride), (β-glucanase), and SP249 (A. niger), and Cereflo (Bacillus subtilis). The respective β-glucanase activities of the five enzymes, as determined by Rotter et al. (1990) using a sugar-reducing method, were 642, 210, 194, 108, and 42 U/g. It is noteworthy that these crude enzyme preparations, in addition to having β-glucanase activity, also contained other unreported enzyme activities that could also affect chick performance. All of the enzymes at 0.003125, 0.00625, and 0.0125% were added to the experimental diet for the dose-response study. Performance per chick was recorded at 14 d of age.

Another data set used in the first study was obtained from Zhang et al. (1996). In this experiment, 1-d-old Single Comb White Leghorn cockerels were fed a commercial starter diet for a 7-d pre-experimental period. The experimental diets were fed to birds from 7 to 21 d of age. The diet consisted of the following ingredients: 60% rye, 8.25% wheat, 24.5% soybean meal, and 6.75% other ingredients. The calculated ME₀ of the diet was 2,950 kcal/kg. Rye grain (Prima) was selected as the substituted cereal for wheat in the diet because rye contains high levels of viscous arabinoxylans. The arabinoxylans in rye grains are primarily responsible for their antinutritive effects (Antoniou et al., 1991). They greatly reduce chick performance but are efficiently hydrolyzed by enzyme preparations containing xylanase activity (Fengler et al., 1988; Fengler and Marquardt, 1988; Marquardt et al., 1994; Zhang et al., 1996, 1997, 2000a). Two enzyme preparations, RM1 (T. longibrachiatum) and NQ (T. ressei), were used in this study (Zhang et al., 1996). The xylanase activity of RM1 was 389 U/g and that for NQ was 778 U/g of enzyme preparation, as assayed by the azo-dye method (McCleary, 1992) with dye-labeled arabinoxylan as the substrate. Different amounts of RM1 (0, 0.25, 0.75, 2.75, 6.75, 20.25 g/kg) and NQ (0, 0.1, 0.3, 0.9, 2.7, and 8.1 g/kg) were added to the diet, at the expense of rye, for 12 different treatments. Bird weight and feed consumption based on six birds were recorded 4 h after removal of feed at 21 d of age.

The data for the second study were obtained from Experiment 2 (Marquardt et al., 1994). In this experiment, 1-d-old Single Comb White Leghorn chicks were fed a commercial starter diet for a 7-d pre-experimental period. The experimental diets were fed to birds from 7 to 21 d of age in a factorial arrangement of treatments: 4 (cereals) × 4 (enzyme doses). The cereals used in four diets were 63% corn (unknown variety), 67% wheat (Kapetwa), 66% hulless barley (Scot), and 64% rye (Prima), respectively. The calculated ME₀ of the four diets were 3,027, 3,196, 2,979, and 2,971.
kcal/kg. The diets were supplemented with different concentrations (0, 0.5, 1, and 2 g/kg) of a crude enzyme preparation, Kyowa Cellulase (T. reesei). The xylanase and cellulase activities as determined by the Japan Food Laboratory were 1,500 and 1,000 U/g, respectively. The chick performances based on a bird basis were recorded at 21 d of age.

The data for the third study were obtained from Bedford and Classen (1992). In this experiment, 1-d-old male broiler chicks were fed one of four diets supplemented with different amounts of a pentosanase preparation (experimental product from T. longibrachiatum) in a 4 × 6 factorial arrangement of treatments from 1 to 19 d of age. The diets consisted of the following proportions of rye (Musketeer) and wheat (unknown variety): 0:60, 20:40, 40:20, and 60:0 each with 32.05% soybean meal, and 7.95% other ingredients. The calculated MEₚ of the four diets were 3,072, 2,988, 2,905, and 2,821 kcal/kg, respectively. The enzyme preparation added to each of the four diets was 0, 1, 2, 4, 8, and 16 g/kg. The xylanase activity of this enzyme preparation was 2,150 U/g as determined using a sugar-reducing method when assayed on oat spelt xylan (Seeta et al., 1989). Chick performances, based on six birds, were recorded at 19 d of age.

For demonstration purposes, the price range for enzyme preparations was assumed to be US $3 to $7/kg. The prices for corn, wheat, barley, and rye were assumed to be $0.13, $0.12, $0.08, and $0.08/kg, respectively. The barley and rye were used as substituted cereals for corn or wheat in the diet, therefore, their price was assumed to be less expensive than that of wheat. The average price of other ingredients in a diet was $0.08/kg, and the price of chickens was $1.23/kg. Other prices can be inserted into the equations as desired as outlined below.

Outline of a Multipurpose Feed Enzyme Analyzer (MPFEA)

We have developed a log-linear model equation to predict the performance of chickens fed a cereal-based diet supplemented with different concentrations of a feed enzyme (Zhang et al., 1996, 2000b). The model can estimate maximal economic return when a feed enzyme is added to a diet. Based on the log-linear model, we have further developed a software package, a MPFEA. The MPFEA comprises two parts: a modeling part and an application part (Figure 1). The modeling part contains revenue, production cost, and profit functions.

The MPFEA has three applications. The first is to evaluate the profitability of different enzyme preparations when added to a specific diet and determines the most profitable cereal for a specific enzyme preparation based on maximal economic returns. The second is to determine the optimal amount of a feed enzyme and a cereal used in a diet to obtain maximal profit. The third is to determine the alternate price that should be paid for a given enzyme preparation and a cereal.

Principle of the MPFEA: Maximal Profit with Optimal Inputs

From the dose-response study with varying the levels of a feed enzyme added to a diet, the log-linear model equation was selected to fit the data of the output or chick performance and the input or amount of enzyme. The general model equations, as proposed by Zhang et al. (2000b) for weight gain (Equation 1) and feed intake (Equation 2), were as follows:

\[ WG = A + B \log (C X_E + 1) \]  
\[ FI = a + b \log (c X_E + 1) \]

where \( X_E \) = amount of an enzyme (percentage of diet); \( WG \) = weight gain (g); \( FI \) = feed intake (g); and \( A, B, C \) and \( a, b, c \) = corresponding coefficients of the two regression equations, respectively. Based on the two equations, we have developed a general profit function (Equation 3):

\[ \Pi = WG \cdot P_y - FI \cdot \Sigma (P_i X_i) \]

where \( \Pi \) = profit function; \( P_y \) = price of chickens; \( P_i \) = price of ingredients in a diet; and \( X_i \) = amount (%) of the ith variable such as rye, wheat, enzyme preparation, and other ingredients in a diet. The maximal profit can, therefore, be calculated when the partial derivatives \( \partial \Pi / \partial X_E \) or \( \partial \Pi / \partial X_R \) of Equation 3 to variable \( X_E \) (the amount of enzyme added to a diet) or \( X_R \) (the amount of substituted cereal, such as rye, added to a diet) are equal to zero (Heady and Dillon, 1961). A more detailed profit equation can be deduced when other variables are utilized (Equation 4). The data set from Bedford and Classen (1992), as an example, can be used to calculate the optimal amounts of a feed enzyme and a substituted cereal (rye) for wheat that should be used in a diet to provide maximal profit. This value can be determined using the following optimization models:

\[ \Pi = WG \cdot P_y - FI \left( P_W X_W + P_R X_R + P_E X_E + P_O X_O \right) \]

where \( \Pi \) is the profit function ($/kg) and \( WG \) (weight gain, kg) and \( FI \) (feed intake, kg) are the regression Equations 1 and 2 for estimating the revenue function (\( WG \cdot P_y \)) and the cost function \( (P_W X_W + P_R X_R + P_E X_E + P_O X_O) \) in Equation 4. We let \( P_y \) ($/kg) = price of chicken per kilogram, \( P_w \) = price of wheat per kilogram, \( P_R \) = price of rye per kilogram, \( P_E \) = price of enzyme per kilogram, and \( P_O \) = price of other ingredients per kilogram. Assume wheat is a standard cereal used in a diet, and rye, an inexpensive cereal relative to wheat, is selected as a substitute cereal for wheat. The percentages of wheat (\( X_W \)), rye (\( X_R \)), feed enzyme (\( X_E \)), and other ingredients (\( X_O \)) in a diet are the decision variables of the equation. In addition, the constraints of the equation are set as follows:

\[ X_R + X_W = 60 \]  
\[ X_E + X_O = 40 \]  
\[ X_R + X_W + X_E + X_O = 100 \]  
\[ 0 \leq X_R \leq 60 \]  
\[ 0 \leq X_E \leq 2 \]
The coefficients (A, B, C or a, b, c) for the log-linear model for weight gain or feed consumption for the data from the first and second study were calculated using a program developed by Zhang et al. (2000b). A multiple regression analysis was used for the data from the third study to establish the response of chick performances, such as weight gain (WG) and feed intake (FI), to the amount of enzyme (XE) and the amount of rye relative to wheat in the diet as the inputs of the equation, were calculated by the stepwise regression method (SAS, 1994), where the C values of the log-linear equation were assumed to be 2,150. The data for the third study were also analyzed using Sigma Plot (Kuo and Norby, 1992) to determine the level of profit obtained with different amounts of an enzyme and different proportions of a substituted cereal in a diet, such as rye substituted for that of wheat.

The standard errors of means for all of the data are given in the original studies. The residual standard deviations of regression for the log-linear model equations are listed in Table 1.

**RESULTS AND DISCUSSION**

**Evaluating the Profitability of Different Feed Enzymes**

One of the problems encountered by nutritionists in the feed industry is how to select a feed enzyme that would be most effective for a particular feed. The effect of different feed enzymes are generally evaluated by biological criteria such as their effect on chick performance, digestibility of feed nutrients, and degree of reduction of the viscosity of digesta or the diet (Bedford and Classen, 1992; Joroch et al., 1995; Zhang et al., 1996, 2000a).
In most studies, comparisons among different enzyme preparations have been carried out using the same amounts of different enzyme preparations in a cereal-based chick diet, as determined by an enzyme activity assay or the levels of inclusion in the diet as recommended by the manufacturers (Rotter et al., 1989; Guenter 1997; Boros et al., 1998; Zhang et al., 2000b). However, it is difficult to correctly evaluate different enzyme preparations based on their activities, because many enzyme preparations are from different sources. Therefore, they often contain a different spectrum of enzymes with different catalytic properties. In addition, the selection of the proper assay conditions such as pH, especially when comparing the activity of different feed enzymes, is essential because the selected pH will bias results in favor of an enzyme whose optimal pH is closest to the selected pH, which may not be the optimal pH in vivo (Marquardt and Bedford, 1997; Ziggers, 1999; Zhang et al., 2000a).

Recently, we have developed a new approach to accurately evaluate the effects of different enzyme preparations. The approach uses a new concept for estimating the efficacy of a feed enzyme: the slope of a log-linear model equation (Zhang et al., 1996, 2000b). This evaluation, although very useful, is based on the biological data only. However, the goal of many studies is often to select an enzyme preparation that will yield the greatest profit.

The objective of the first study was to determine if the effects of different feed enzyme preparations on maximal profits could be evaluated using the MPFEA. The profit functions (Table 1) were readily derived using Equation 4 from the production (Equation 1) and feed consumption (Equation 2) functions. The maximal profit and the optimal amount of an enzyme that should be added to a diet were calculated using Equations 4 to 10. The results in Table 2 indicated that the maximum profits per 1,000 birds when given the optimal amount of each of the five enzyme preparations, Cellulase Tv, Celulast, Finizym, Cereflo, and SP249 were $67.29, $61.27, $51.91, $49.27, and $46.79, respectively. In this analysis, the assumed prices of the enzymes were the same. The sequence of these values also agrees with that of the B values for the feed to gain ratio as determined from the log-linear equation ($r^2 = 0.99, P < 0.0005$). The same trend was also observed in this study using data from Zhang et al. (1996).

These results, in contrast to subsequent results with different cereals or cereals plus enzymes, suggest that both the B values and the maximal profit provided similar indices for the evaluation of different enzyme preparations. This relationship, however, would not necessarily be the same if the prices of the different enzyme preparations varied. In addition, the advantage of the two methods, especially for the method using maximal profit, is that they do not require knowledge of enzyme activity, the combination of enzymes used in a preparation, or the site of action of the enzymes in the gut. The requirements for latter method (the maximal profit) are 1) that the model equations be used to establish the influence of different concentrations of different enzyme preparations on chick

<table>
<thead>
<tr>
<th>Cereal (enzyme)</th>
<th>WG (g)</th>
<th>r</th>
<th>SD</th>
<th>Fl (g)</th>
<th>r</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley (CT)</td>
<td>31.4 + 7.68 log (10^5 X + 1)</td>
<td>0.99</td>
<td>0.03</td>
<td>80.2 + 7.27 log (10^5 X + 1)</td>
<td>0.99</td>
<td>1.67</td>
</tr>
<tr>
<td>Barley (CC)</td>
<td>31.0 + 6.79 log (10^5 X + 1)</td>
<td>0.99</td>
<td>0.04</td>
<td>80.1 + 7.72 log (10^5 X + 1)</td>
<td>0.99</td>
<td>0.66</td>
</tr>
<tr>
<td>Barley (FZ)</td>
<td>30.8 + 4.99 log (10^5 X + 1)</td>
<td>0.99</td>
<td>1.06</td>
<td>79.9 + 5.75 log (10^5 X + 1)</td>
<td>0.99</td>
<td>0.28</td>
</tr>
<tr>
<td>Barley (CF)</td>
<td>30.3 + 4.49 log (10^5 X + 1)</td>
<td>0.92</td>
<td>3.21</td>
<td>79.3 + 6.41 log (10^5 X + 1)</td>
<td>0.93</td>
<td>3.28</td>
</tr>
<tr>
<td>Barley (SP)</td>
<td>30.6 + 4.00 log (10^5 X + 1)</td>
<td>0.96</td>
<td>1.91</td>
<td>79.5 + 4.63 log (10^5 X + 1)</td>
<td>0.94</td>
<td>2.94</td>
</tr>
<tr>
<td>Rye (RM1)</td>
<td>536 + 45.6 log (10^3 X + 1)</td>
<td>0.99</td>
<td>7.3</td>
<td>1,309 + 45.6 log (10^3 X + 1)</td>
<td>0.98</td>
<td>13.4</td>
</tr>
<tr>
<td>Rye (NQ)</td>
<td>549 + 52.2 log (10^3 X + 1)</td>
<td>0.98</td>
<td>13.1</td>
<td>1,317 + 59.6 log (10^3 X + 1)</td>
<td>0.94</td>
<td>26.2</td>
</tr>
<tr>
<td>Corn (KC)</td>
<td>135 + 1.67 log (10^4 X + 1)</td>
<td>–0.96</td>
<td>0.9</td>
<td>275 – 1.16 log (10^10 X + 1)</td>
<td>–0.83</td>
<td>4.3</td>
</tr>
<tr>
<td>Wheat (KC)</td>
<td>125 + 0.81 log (10^10 X + 1)</td>
<td>0.98</td>
<td>0.8</td>
<td>248 + 0.43 log (10^10 X + 1)</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Barley (KC)</td>
<td>113 + 2.26 log (10^10 X + 1)</td>
<td>0.99</td>
<td>2.0</td>
<td>220 + 4.87 log (10^10 X + 1)</td>
<td>0.99</td>
<td>0.3</td>
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<tr>
<td>Rye (KC)</td>
<td>97 + 8.76 log (10^4 X + 1)</td>
<td>0.99</td>
<td>0.3</td>
<td>220 + 9.09 log (10^4 X + 1)</td>
<td>0.99</td>
<td>2.0</td>
</tr>
<tr>
<td>0% Rye (PP1)</td>
<td>399 + 35.5 log (10^10 X + 1)</td>
<td>0.81</td>
<td>11.4</td>
<td>664 + 13.1 log (10 X + 1)</td>
<td>0.52</td>
<td>10.7</td>
</tr>
<tr>
<td>20% Rye (PP)</td>
<td>359 + 6.28 log (10^4 X + 1)</td>
<td>0.99</td>
<td>2.5</td>
<td>622 + 8.01 log (10^4 X + 1)</td>
<td>0.57</td>
<td>20.1</td>
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<tr>
<td>40% Rye (PP)</td>
<td>306 + 2.16 log (10^6 X + 1)</td>
<td>0.98</td>
<td>9.2</td>
<td>561 + 30.8 log (10^4 X + 1)</td>
<td>0.93</td>
<td>21.0</td>
</tr>
<tr>
<td>60% Rye (PP)</td>
<td>232 + 54.4 log (10^3 X + 1)</td>
<td>0.98</td>
<td>13.7</td>
<td>530 + 63.7 log (10^3 X + 1)</td>
<td>0.94</td>
<td>20.6</td>
</tr>
</tbody>
</table>

A–D: Data from four studies were used to develop the prediction equation for weight gain, WG = A + B log (C X + 1), and feed consumption, Fl = a + b log (c X + 1), where X = amount of an enzyme (%) added to a cereal-based diet; and A, B, C, and a, b, c = coefficients of the log-linear equations for weight gain and feed consumption, respectively. The performances of chicks predicted by the equations were the values per bird when Leghorns were fed from 7 to 14 d (A: Rotter et al., 1989) and from 7 to 21 d (C: Marquardt et al., 1997), and the values per six birds when Leghorns were fed from 7 to 21 d (B: Zhang et al., 1996), and when broilers were fed from 1 to 19 d (D: Bedford and Classen, 1992). The relative proportion of rye and wheat in the different diets were 0, 60; 20, 40; 40, 20; and 60, 0.

1WG = weight gain; Fl = feed intake.

2The enzyme preparations used in the studies were RMI and PP (a pentasolans preparation) from Finnfeed International Ltd; NQ and KC (Kyowa Cellulase) from Nutri-Quest; CT (Cellulase Tv concentrate) from Miles Laboratories Inc.; and CC (Celluclast), FZ (Finizym), CF (Cereflo), and SP (SP249) from Novo A/S Denmark.

3SD represents the residual standard deviation of regression for the log-linear equations.
performance and 2) that the price of the major ingredients in a diet be used. The method proposed in this study therefore provides a simple way to evaluate the collective effect of different enzyme preparations when incorporated into chick diets based on maximal economic returns.

### Identifying the Most Profitable Cereal When Used with a Feed Enzyme

Based on the proposed method (Zhang et al., 1996, 2000b), the most suitable cereal for a target enzyme preparation can be determined from the slope of a log-linear model equation. In this study (Study 2), the B values for the feed to gain ratio were calculated from the data of Marquardt et al. (1994). The sequence of cereals producing the greatest response to an enzyme preparation in decreasing order were rye, barley, wheat, and corn (negative control) (Table 3). However, the sequence of the cereals that yielded the maximum profit after enzyme addition was different. The maximal profits obtained when the enzyme preparation was added to a barley-, corn-, wheat-, and rye-based diet were $135.00, $134.45, $133.55, and $123.96 per 1,000 birds, respectively, when the price of all cereals were the same (Table 3). Therefore, under these conditions, the relationship between the magnitude of the B values for feed to gain ratio and the maximal profit was low ($r^2 = 0.61, P = 0.2171$). This disagreement was also observed in the third study ($r^2 = 0.59, P = 0.2340$). The reason for this discrepancy is attributed to the fact that the B values reflect the overall response of chicks to different amounts of an enzyme added to different cereal-based diets. The maximal profits are affected not only by the efficacy of the enzyme (B value), and the response of chick when fed different cereal-based diets without enzyme addition (A), but also by the cost of the feed and the enzyme.

The results therefore demonstrate that the latter method (maximal profit) is more useful than the former procedure (B value) for the feed or enzyme industry in determining which cereal should be used with a given feed enzyme to obtain the maximum profit. In addition, if the prices of wheat and corn are assumed to be $0.12 and $0.13/kg, wheat will yield a greater profit than corn, and the rye grain at $0.08/kg becomes a competitive cereal with wheat or corn ($123.96 per 1,000 birds for rye vs. $126.00 or $126.73 per 1,000 birds for corn or wheat). These results demonstrate that the price of a cereal also influences profitability when a special feed enzyme is added to the cereal-based diet. Therefore, an acceptable price for a sub-

<table>
<thead>
<tr>
<th>Source of data</th>
<th>Enzyme preparation</th>
<th>B Value</th>
<th>Optimal enzyme</th>
<th>Maximal profit ($/1,000 birds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotter et al., 1989</td>
<td>Cellulase Tv</td>
<td>-0.247</td>
<td>0.656</td>
<td>67.29</td>
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<tr>
<td></td>
<td>Celluclast</td>
<td>-0.211</td>
<td>0.560</td>
<td>61.27</td>
</tr>
<tr>
<td></td>
<td>Finizym</td>
<td>-0.172</td>
<td>0.452</td>
<td>51.91</td>
</tr>
<tr>
<td></td>
<td>Cereflo</td>
<td>-0.171</td>
<td>0.439</td>
<td>49.27</td>
</tr>
<tr>
<td></td>
<td>SP249</td>
<td>-0.139</td>
<td>0.385</td>
<td>46.79</td>
</tr>
<tr>
<td>Zhang et al., 1996</td>
<td>RM1</td>
<td>-0.0943</td>
<td>0.315</td>
<td>101.19</td>
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<tr>
<td></td>
<td>NQ</td>
<td>-0.0963</td>
<td>0.348</td>
<td>104.38</td>
</tr>
</tbody>
</table>

1The assumed price for enzyme preparations used in the two studies was $5/kg (US $).
2The enzyme preparations used in the study of Rotter et al. (1989) and Zhang et al. (1996) were Cellulase Tv concentrate (Trichoderma viride) from Miles Laboratories Inc.; Cellucast (T. reesei), Finizym (Aspergillus niger), Cereflo (Bacillus subtilis), and SP249 (Aspergillus niger) were from Novo A/S Denmark; RM1 (T. longibrachiatum) was from Finnfeeds International Ltd.; and NQ (T. reesei) was from Nutri-Quest.
3The B values were the slope of log-linear model equation calculated from the feed to gain ratio data. The values are the indexes of the efficacy of a feed enzyme added to a diet (Zhang et al., 1996, 2000b).
4Amounts of enzyme to yield a maximum profit.

### Table 3. Effect of cereal prices on optimal amounts of an enzyme added to different cereal-based diets and their maximal profits

<table>
<thead>
<tr>
<th>Cereal</th>
<th>Value of B</th>
<th>Same price ($/kg)</th>
<th>Optimal enzyme (%)</th>
<th>Maximal profit ($/1,000 birds)</th>
<th>Different price ($/kg)</th>
<th>Optimal enzyme (%)</th>
<th>Maximal profit ($/1,000 birds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>0.05</td>
<td>0.08</td>
<td>0</td>
<td>134.5</td>
<td>0.13</td>
<td>0</td>
<td>126.0</td>
</tr>
<tr>
<td>Wheat</td>
<td>-0.03</td>
<td>0.08</td>
<td>0.0339</td>
<td>133.6</td>
<td>0.12</td>
<td>0.0335</td>
<td>126.7</td>
</tr>
<tr>
<td>Barley</td>
<td>-0.04</td>
<td>0.08</td>
<td>0.0815</td>
<td>135.0</td>
<td>0.08</td>
<td>0.0814</td>
<td>135.0</td>
</tr>
<tr>
<td>Rye</td>
<td>-0.09</td>
<td>0.08</td>
<td>0.3419</td>
<td>124.0</td>
<td>0.08</td>
<td>0.3419</td>
<td>124.0</td>
</tr>
</tbody>
</table>

The B values are the slope of log-linear model equation calculated from the feed to gain ratio data (Zhang et al., 1996, 2000b). The values are indices of the efficacy of a feed enzyme when added to different diets.

These values represent the price of the cereals. The assumption was that the enzyme (Kyowa Cellulase, Finnfeeds International Ltd.) cost was $5/kg (US $).

The optimal amount of enzyme calculated is as the amount of enzyme that yields maximal profits.

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The results therefore demonstrate that the latter method (maximal profit) is more useful than the former procedure (B value) for the feed or enzyme industry in determining which cereal should be used with a given feed enzyme to obtain the maximum profit. In addition, if the prices of wheat and corn are assumed to be $0.12 and $0.13/kg, wheat will yield a greater profit than corn, and the rye grain at $0.08/kg becomes a competitive cereal with wheat or corn ($123.96 per 1,000 birds for rye vs. $126.00 or $126.73 per 1,000 birds for corn or wheat). These results demonstrate that the price of a cereal also influences profitability when a special feed enzyme is added to the cereal-based diet. Therefore, an acceptable price for a sub-
Optimal Amounts of Enzyme and Cereal that Should Be Used in a Diet

One of the important applications of MPFEA is to determine the amounts of an enzyme and a cereal that should be used in the diet to obtain a maximum profit. Generally, the performance response of chicks fed a diet with increasing amounts of an enzyme is a hyperbolic or saturated response pattern. Equal incremental amounts of enzyme, when added to a diet, result in diminishing incremental changes in chick performance (Friesen et al., 1991; Bedford and Classen, 1992; Marquardt et al., 1994; Zhang et al., 1996). However, this study demonstrates that the dose-response of profit obtained with the addition of a feed enzyme yields a quadratic rather than a hyperbolic pattern.

The results, as shown in Figures 2 and 3, indicate that the profit obtained with increasing amounts of a feed enzyme was increased to a certain point. After that, the profit decreased with increasing amounts of the enzyme (Figures 2 and 3). This point can be readily calculated using the MPFEA. The results demonstrated that the optimal amounts of different enzyme preparations that should be added to a diet (Table 2) were considerably different for a given feed enzyme when added to different cereal-based diets (Table 3) and for a feed enzyme when added to a diet with varying the proportions of two cereals (Table 4). These results, however, demonstrated that there was a high correlation between the values of B for feed to gain ratio and the optimal amount of an enzyme that should be used in a diet ($r^2 = 0.89$, $P < 0.06$ for the third study, Table 4). Therefore, the amount of an enzyme that should be used in a diet to obtain maximal profit increases with an increasing B value for the feed to gain ratio. In addition, the optimal amounts of the two inputs to obtain maximum profit can also be determined by the MPFEA, as shown by the arrows indicated in Figure 4. The two variables used in this study were variable amounts of enzyme and variable proportions of rye and wheat.

**Profit Contours or Isoquants**

The objective of obtaining maximal profit by enzyme addition to a given diet may not be the only goal for a feed company or poultry farm. In some cases, the question that has to be asked is, does the enzyme and substituted cereal, used at various levels and in different combinations, give the expected profit? The relationships among amounts of enzyme added to the diet, the relative concentrations of two cereals (rye vs. wheat), the cost of the enzyme...
preparation, and the resulting profit are illustrated in Figure 4. The two-dimensional figures on the right side of Figure 4 represent the contour of response associated with horizontal slices of the figure on the left. These lines, called profit contours or isoquants, provide a useful tool to determine any combination of inputs such as amounts of an enzyme and rye used in a diet for any fixed level of profit. For example, if the price of enzyme was $5/kg (middle figure), it is possible to obtain $65 (line labeled 65) of profit per 1,000 birds with various combinations of rye (from 7 to 38%) and an enzyme (from 0 to 1.6 %). The arrows (Δ) in the figures indicate the amount of enzyme that should be used to yield maximal profits. For example, maximum profits of $71.72, $71.27, or $70.98 per 1,000 birds were obtained when the enzyme was at 0.27, 0.16, or 0.11%; the rye was at 0, 0, or 0%; and enzyme cost was $3, $5, or $7/kg, respectively. Different combinations of these inputs represent the optimal amounts of the enzyme and the rye that should be used in the diet to obtain maximum profits.

**Decision for Price of Enzyme and Cereal Used**

There are many factors that influence the profit obtained when a feed enzyme is added to a diet. They include the amount of enzyme added, the type and amount of cereals, the efficacy of the feed enzyme, and the price of enzyme and cereals used. Once the profit function is established, any variable in the equation can be calculated and analyzed provided other variables are fixed. Therefore, the price that should be paid for an enzyme and a substituted cereal for wheat in diets.

### Table 4: Effect of price of an enzyme and cereals on the maximal profits and the optimal amounts of an enzyme added to diets with different proportion of rye

<table>
<thead>
<tr>
<th>Rye in diets</th>
<th>B value</th>
<th>Price of enzyme ($/kg)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$3</td>
<td>$5</td>
<td>$7</td>
<td>$3</td>
<td>$5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.02</td>
<td>$0.04</td>
<td>$0.02</td>
<td>$0.04</td>
<td>$0.02</td>
</tr>
<tr>
<td>0%</td>
<td>-0.0323</td>
<td>0.273</td>
<td>0.273</td>
<td>0.159</td>
<td>0.159</td>
<td>0.113</td>
</tr>
<tr>
<td>20%</td>
<td>-0.0482</td>
<td>0.461</td>
<td>0.462</td>
<td>0.271</td>
<td>0.271</td>
<td>0.191</td>
</tr>
<tr>
<td>40%</td>
<td>-0.0544</td>
<td>0.738</td>
<td>0.742</td>
<td>0.435</td>
<td>0.438</td>
<td>0.309</td>
</tr>
<tr>
<td>60%</td>
<td>-0.1867</td>
<td>1.262</td>
<td>1.272</td>
<td>0.748</td>
<td>0.754</td>
<td>0.537</td>
</tr>
</tbody>
</table>

|          |         |           |  |  |  |  |
| 0%       | -0.0323 | 71.72     | 71.72 | 71.27 | 71.27 | 70.98 | 70.98 |
| 20%      | -0.0482 | 68.15     | 68.59 | 67.4  | 67.83 | 66.91 | 67.34 |
| 40%      | -0.0544 | 65.21     | 66.07 | 64.01 | 64.86 | 63.23 | 64.08 |
| 60%      | -0.1867 | 63.27     | 64.58 | 61.19 | 62.48 | 59.85 | 61.13 |

1. This price presents the net difference between the prices (US $) of wheat and rye. Rye was assumed as an inexpensive and substituted cereal for wheat in diets.
2. The corresponding amount of wheat in the four diets was 60, 40, 20, and 0%, respectively.
3. The B values were the slope of log-linear model equation calculated from the data of feed to gain ratio. The values are indexes of the efficacies of a feed enzyme when added to a diet with different levels (Zhang et al., 1996, 2000b).

For example, the only way that Finizym could yield the same maximal profit as CT would be to improve its efficacy (B value). The results indicated that an 82% decrease in the price of CC ($5 to $0.9) would be required to yield the same maximal profit ($67.29 per 1,000 birds) as obtained with CC at $5/kg. However, the same results could be obtained with a 17% improvement in the efficacy of CC as an increase in its B value for the feed to gain ratio from −0.211 to −0.247. This result suggests that an improvement in the efficacy of an enzyme is much more effective in increasing profitability than is reducing the price. In some cases, it is not possible to obtain an equivalent maximal profit by changing the price of a feed enzyme. For example, the only way that Finizym could yield the same maximal profit as CT would be to improve its efficacy, i.e., improvement of its B value from −0.212 to −0.247 as shown in Table 2.

In addition, the maximal profit is also influenced by the price of the cereal used in a diet. As indicated in Table 3, rye grain cannot compete with wheat when the prices of these cereals are the same. However, when a higher price of wheat was used, rye grain could yield a similar maximal profit to that obtained with wheat. The result suggests that as the prices of alternate grains decrease in value relative to the prices of standard grains such as corn or wheat, more expenditure for enzyme supplementation could be...
FIGURE 4. Effect of different combinations of two variables, amounts of enzyme ($X_E$) and rye ($X_R$) added to diets on the profit of chickens fed diets from 1 to 19 d of age. Cereals in the diet were wheat plus rye (60%). The profit functions were as follows: $\Pi = WG \cdot Py - FI \sum (Pi \cdot Xi)$, where $WG = (404 - 2.04X_R + 5.25 \times 10^{-2}X_E^2 - 3.20 \times 10^{-3}X_R^2 + 9.78 \times 10^3 - 1.29 \times 10^{-2}X_E^2 + 2.10 \times 10^{-3}X_R^2) \log (2150 \cdot X_E + 1)$, and $FI = (648 - 8.52 \times 10^{-2}X_R^2 + 8.33 \times 10^{-3}X_E^2 + 2.64 + 2.27 \times 10^{-2}X_R^2 - 2.10 \times 10^{-3}X_E^2) \log (2150 \cdot X_E + 1)$; $\Pi =$ profit function ($\$/1,000 birds), $WG =$ weight gain (g), $FI =$ feed intake (g), $Py$ and $Pi$ represent the price of chickens and the price of the $i$th ingredient ($Xi$) in a diet. The plots on the left give the three-dimensional relationship for relative amount of rye in the diet (the balance is wheat), the amount of enzyme added to the diet, and the profits obtained assuming wheat and rye prices (US $) are $0.12 and $0.08/kg, respectively, and that of enzyme is $3, $5, or $7/kg. The figures on the right are the profit contours of two-dimensional slices of that on the right for diets containing different amounts of enzyme and different percentage of rye in the diet. The number in each line represents the fixed profit that could be obtained by feeding different amounts (%) of rye and enzyme. The arrow indicates the amount of enzyme that should be used to obtain maximal profits. Data used for the calculations were from Bedford and Classen (1992).
justified to bring the final profit closer or equivalent to that obtained by the use of standard grains. This strategy could also be used by a feed industry to determine the expected price of a target cereal in order to obtain a certain level of maximal profit.

In conclusion, the MPFEA that was developed in this study can be used by the enzyme and feed industries to evaluate different enzyme preparations based on their profitability, to determine the maximal economic return that can be obtained with the optimal inputs of feed ingredients such as type and amounts of cereals and enzymes, and to analyze the relationship between the price of a feed enzyme or a cereal and the economic return. This study demonstrates that a knowledge of nutrition in combination with computer technology and the modeling method can provide nutritionists and managers in the enzyme and feed industry with useful information for their research activities and business decisions.

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