J. Dairy Sci. 98:1225–1233
http://dx.doi.org/10.3168/jds.2014-8810

Feeding of by-products completely replaced cereals and pulses in dairy cows and enhanced edible feed conversion ratio

P. Ertl,*[1] Q. Zebeli,† W. Zollitsch,* and W. Knaus*
*Department of Sustainable Agricultural Systems, Division of Livestock Sciences, BOKU–University of Natural Resources and Life Sciences, 1180 Vienna, Austria
†Department for Farm Animals and Veterinary Public Health, Institute of Animal Nutrition and Functional Plant Compounds, University of Veterinary Medicine, 1210 Vienna, Austria

ABSTRACT

When fed human-edible feeds, such as grains and pulses, dairy cows are very inefficient in transforming them into animal products. Therefore, strategies to reduce human-edible inputs in dairy cow feeding are needed to improve food efficiency. The aim of this feeding trial was to analyze the effect of the full substitution of a common concentrate mixture with a by-product concentrate mixture on milk production, feed intake, blood values, and the edible feed conversion ratio (eFCR), defined as human-edible output per human edible input. The experiment was conducted as a change-over design, with each experimental period lasting for 7 wk. Thirteen multiparous and 5 primiparous Holstein cows were randomly assigned to 1 of 2 treatments. Treatments consisted of a grass silage-based forage diet supplemented with either conventional ingredients or solely by-products from the food processing industry (BP). The BP mixture had higher contents of fiber and ether extract, whereas starch content was reduced compared with the conventional mixture. Milk yield and milk solids were not affected by treatment. The eFCR in the BP group were about 4 and 2.7 times higher for energy and protein, respectively. Blood values did not indicate negative effects on cows' metabolic health status. Results of this feeding trial suggest that by-products could replace common concentrate supplements in dairy cow feeding, resulting in an increased eFCR for energy and protein which emphasizes the unique role of dairy cows as net food producers.
Key words: organic, dairy cow, efficiency, by-product, feed conversion

INTRODUCTION

Global crop demands are predicted to increase about 100 to 110% by the year 2050 (from 2005 as baseline year) and concerns about future food security are rising (Godfray et al., 2010; Tilman et al., 2011). This reinforces pressure on livestock systems because animals are very inefficient in converting feed into animal products (Bradford, 1999). According to Cassidy et al. (2013), 89% of crop-produced calories fed to animals are lost and do not recur as human food in form of animal products. However, when fed human-inedible feed, livestock can provide a net gain in food supply (CAST, 1999). With their ability to convert human-inedible fibrous plant substrates into high-quality animal products, ruminants have always played a unique role in animal agriculture. However, the high performance levels of modern dairy cows have made it necessary to feed high amounts of grains and pulses to dairy cows, which also lead to an increase in the feed versus food competition between dairy cows and humans (Knaus, 2009, 2013).

Wilkinson (2011) introduced the concept of the edible feed conversion ratio (**eFCR**) to compare human-edible input versus output. Oltjen and Beckett (1996) were the first to analyze dairy cow rations in terms of food balance. Their results showed that, for cows receiving 50% concentrates, the human-edible food output in form of meat and milk was lower than the potentially human-edible input with feeds (57 and 96% for energy and protein, respectively). In other words, these cows consume more human food than they produce. In this debate, the potential of by-products to improve food balances of dairy production has been addressed several times (Eastridge, 2006; CAST, 2013; Gill, 2013). Bradford (1999) attributed the global supply of by-products within a year the potential to energetically support 500 million tons of milk production. According to Bocquier and González-García (2010), using by-products as feed is also a strategy to become less dependent on cereals and oil seeds, which will become more important in human nutrition in the future.

By-products strongly vary in their chemical composition, and their effect on milk yield and other production indicators depends markedly on the type and amount of the by-product included in the ration. In general,

Received September 3, 2014.
Accepted October 27, 2014.
[1]Corresponding author: paul.ertl@boku.ac.at

by-products differ from common concentrates mainly in their starch and fiber contents. Inclusion of by-products in dairy diets is discussed differently in the literature. For example, earlier studies reported higher forage DMI associated with greater milk yield of cows fed fibrous by-products versus starchy concentrates (Thomas et al., 1986; Huhtanen, 1993). However, other studies have observed unaffected milk yield despite higher DMI (Phipps et al., 1987; Huhtanen et al., 1995), whereas others reported either no effects on DMI and milk yield (Castle et al., 1981) or a lower DMI and unaffected milk yield (Alamouti et al., 2009). Various by-products have already been analyzed and tested as supplements in dairy cow feeding (Bernard and McNeill, 1991; Mowrey et al., 1999; Bampidis and Robinson, 2006). However, only limited information is available on the potential of by-products to increase the eFCR.

The objective of this study was to examine the potential of by-products to increase eFCR in dairy production. Therefore, a by-product mixture was substituted for a commonly used concentrate mixture in a feeding trial. It was hypothesized that under the conditions of Austrian organic dairy production, by-products as supplements can strongly improve eFCR, without negative effects on feed intake, production traits, metabolic health, and efficiency indicators. To ensure that the lower starch and higher fat and fiber contents of the by-product mixture had no negative effects on animal health, blood variables relative to metabolic status, liver activity, and acute phase response were analyzed.

MATERIALS AND METHODS

Experimental Design and Animals

The experiment was conducted as a change-over design with 2 consecutive experimental periods of equal duration at the organic farm of the secondary agricultural and forestry school Ursprung in the province of Salzburg, Austria (570 m above sea level, 1,250 mm annual precipitation, 8.5°C average annual temperature) between November 2013 and February 2014.

Thirteen multiparous and 5 primiparous Holstein cows, housed in a cubical housing system with Calan gates (American Calan Inc., Northwood, NH) for individual feeding, were randomly assigned to 2 treatment groups of 9 cows each, according to milk yield, days in milk, lactation number, and live weight. At the beginning of the experiment, cows had an average (± SD) milk yield of 27.5 ± 5.1 kg, 683 ± 53 kg of BW, and DIM and number of lactations averaged 108 ± 90 d and 3.1 ± 2, respectively. Prior to the experiment, all cows received grass silage and hay derived from permanent grassland at a ratio of 0.75:0.25 on a DM basis for ad libitum intake, and a maximum of 8 kg fresh matter of commercially available concentrates per cow and day via an automatic feeding station (based on the milk production of the previous week).

Each experimental period lasted for 7 wk, whereby the first 2 wk were used for diet adaptation, and the last 5 wk were used for measurements. Immediately after the end of the first experimental period, treatment groups changed and the adaptation time for the second experimental period started. The first week of the experiment served as adaptation time for the Calan gates. The experimental protocol was approved by the national veterinary authority Salzburg (file number 20403–25/2/324–2013).

Dietary Treatments and Feeding Procedure

Cows were fed diets containing the same forages but differing in their concentrate mixtures. The composition of the forage and the ingredients of different concentrate mixtures, as well as their estimated proportion of human edible contents, are shown in Table 1. The ingredients of the mixture for the control group (**CON**) were crops commonly used in Austrian organic dairy cow feeding. The experimental by-product concentrate mixture (**BP**) included only by-products from the human food processing industry, which were available in organic quality in appropriate amounts. Control and BP mixtures were obtained from a commercial feed manufacturer and composed to be isoenergetic and isonitrogenous. Both treatment groups received a forage mixture for ad libitum intake, consisting of 0.75 grass silage and 0.25 alfalfa hay on a DM basis. The forage mixture was prepared once a day and offered twice daily in an amount to ensure approximately 10% of fresh matter feed refusals. Grass for silage production was first-cut, harvested from 6.5 ha of perennial clover-grass (approximately 50% grasses and 50% clover), 3.5 ha of permanent grassland (about 50% grasses, 30% herbs, and 20% legumes), and 2.5 ha of perennial rye.

Due to unfavorable weather conditions in Austria in 2013, the first-cut of artificially dried alfalfa hay was purchased from Italy. Chemical composition of both concentrate mixtures and the forage mixture are shown in Table 2. In both treatments, cows exceeding a daily milk yield of 14 kg received the respective concentrate mixture in pelleted form at a rate of 0.4 kg of DM per additional kilogram of milk via an automatic feeding station. These quantities were adjusted weekly and cows received a maximum of 8 kg of DM concentrate per day.

Data Collection and Analytical Procedure

Cows were milked twice a day at 0600 and 1630 h in a 2 × 3 herring milking parlor. Daily milk yield and

Table 1. Ingredients of forage and concentrate mixtures (g/kg of DM) and their estimated human-edible proportion based on Wilkinson (2011)

Item	Forage mixture	Concentrate mixture[1]		Human-edible proportion
		CON	BP	
Grass silage first cut	750	—	—	0.0
Alfalfa hay first cut	250	—	—	0.0
Peas	—	270	—	0.8
Corn	—	200	—	0.8
Field beans	—	200	—	0.8
Oats	—	160	—	0.8
Wheat	—	135	—	0.8
Corn middlings	—	—	415	0.2
Beet pulp	—	—	305	0.0
Rapeseed cake	—	—	155	0.1
Soy cake	—	—	90	0.8
Molasses	—	30	30	0.0
Mineral and vitamin mixture	—	5	5	0.0

[1]Mixtures: CON = control concentrate mixture; BP = by-product concentrate mixture.

concentrate intake were documented digitally throughout the experiment, whereas individual forage intake was determined manually during four 6-d recording periods in wk 4, 8, 11, and 15 of the experiment, using Calan gates. During these recording periods, cows were weighed immediately after 2 consecutive milkings, using a digital livestock platform scale (Fellinger Reinhold, Hydraulik & Wiegetechnik, Dresslbrunn, Austria) and the mean was calculated for cows' live weight. In addition, blood samples were taken from each cow from the coccygeal vein on 2 occasions per experimental period (beginning and end) right before the afternoon feeding, using serum sampling tubes (Sarstedt 02.1063, 9 mL with clotting activator, Sarstedt, Nümbrecht, Germany). Samples were instantly put on ice and then centrifuged at 2,500 × *g* for 15 min at room temperature to obtain serum, which was immediately frozen in Eppendorf tubes at −20°C until analysis at the University of Veterinary Medicine, Vienna, Austria. Concentration of haptoglobin in the serum was determined by commercially available bovine ELISA kit according to the method described by Zebeli et al. (2011). Analyses for haptoglobin were performed only for the first sampling date in period 1 and the second sampling date in period 2. Serum concentrations of glucose, BHBA, NEFA, blood urea content, cholesterol, creatinine, and liver enzymes such as aspartate aminotransferase, glutamate dehydrogenase, and gamma-glutamyltransferase (**GGT**) were measured at the Central Laboratory of the University of Veterinary Medicine, Vienna, using standard enzymatic colorimetric analysis with a fully automated analyzer for clinical chemistry (Cobas 6000/c501, Roche Diagnostics GmbH, Vienna, Austria).

Milk samples were taken from each cow weekly at 2 consecutive milkings and conserved with Bronysolv (ANA.LI.TIK. AUSTRIA, Vienna, Austria) until analysis for fat, protein, lactose, milk urea concentrations, and somatic cell count by Milkoscan (Foss Electric, Hillerød, Denmark). The DMI of forages was recorded daily as the difference between the amount of feed of-

Table 2. Chemical composition (± SD) of feeds (g/kg of DM unless stated otherwise)

Item	Forage mixture	Concentrate mixture[1]	
		CON	BP
DM (g/kg)	362 ± 30	873 ± 2	877 ± 1
CP	171 ± 8	186 ± 2	177 ± 2
uCP[2]	137 ± 1	183 ± 1	189 ± 1
Ether extract	31 ± 1	28 ± 2	66 ± 2
Ash	115 ± 4	37 ± 1	60 ± 1
Starch	—	521 ± 2	328 ± 5
NDF	431 ± 8	137 ± 2	239 ± 3
ADF	316 ± 11	77 ± 4	135 ± 6
ADL	54 ± 8	8 ± 0	20 ± 1
NE_L (MJ/kg of DM)	6.05	8.52	8.16

[1]Mixtures: CON = control concentrate mixture; BP = by-product concentrate mixture.
[2]Utilizable CP at the duodenum (GfE, 2001).

fered and feed refusals. The intake of concentrate was electronically recorded from each cow from the automatic feeding station.

In each recording period, the DM content of the fresh forage mixture and feed refusals were determined 3 times by oven drying at 105°C for 32 h. For analysis of feed chemical composition, the following feed samples were taken during each recording period: 2 samples of the fresh forage mixture, each pooled over 2 consecutive days; 1 sample of feed refusals, also pooled over 2 consecutive days; and 1 sample of each concentrate mixture. Feed samples were vacuum-packed and stored at −20°C until analysis according to the methods described by VDLUFA (1993) at a commercial laboratory with the following method numbers: CP: 4.1.2, ether extract: 5.1.1, starch: 7.2.1, NDF: 6.5.1, ADF: 6.5.2, ADL: 6.5.3, and crude ash: 8.1 (VDLUFA 1993). Utilizable CP content at the duodenum (**uCP**) and nutrient balances were estimated according to the methods of the German Society of Nutrition Physiology (GfE, 2001). To calculate NE_L requirements, the method including fat, protein, and lactose content of the milk described by NRC (2001) was used. Edible feed conversion ratios for energy and protein were calculated on a gross energy and CP basis, respectively, and were specified as human-edible output divided by potentially human-edible input. Human-edible output consisted of the amount of gross energy and CP in the milk. To calculate the human-edible input, potentially edible proportions of the different ingredients of the concentrate mixtures were estimated based on Wilkinson (2011) with small modifications for rapeseed cake and beet pulp because we only considered the remaining fat of the rapeseed cake for the edible proportion and no protein extraction and we did not find noteworthy contributions of beet pulp to human nutrition. Peas, maize, field beans, oats, wheat, and soy cake were considered to have an edible fraction of 0.8, whereas edible proportions for maize middlings, rapeseed cake, beet pulp, and molasses were estimated to be 0.2, 0.1, 0.0, and 0.0, respectively. Forages were considered to have no potentially human-edible fraction (Table 1), because we did not consider potential other uses of arable land when estimating edible proportions.

Statistical Analysis

Data were analyzed with the statistical software package SAS using PROC MIXED (SAS Institute Inc., 2009). Except for blood values, the following model was used:

$$Y_{ijklmn} = \mu + T_j + day_k + milk_l + LW_m + DL_n + cow(T)_{ij} + \varepsilon_{ijklmn},$$

where Y_{ijklmn} = studied variable on cow i in treatment j, with milk yield l and live weight m, on day of lactation n; μ = overall mean; T = fixed effect of treatment j (CON, BP); day = fixed effect of day k in the feeding trial; milk = continuous effect of daily milk yield l (not for milk and ECM performance); LW = continuous effect of live weight m (not for milk composition values); DL = continuous effect of day of lactation n (only for milk performance and milk composition values); cow(T) = random effect of cow i within treatment j; ε = random error. The fixed effect of sequence of treatments was tested but was not significant and therefore excluded from the final model.

Blood values were analyzed according to the following model:

$$Y_{ijklm} = \mu + T_j + SD_k + period_l + DL_m + T_j \times SD_k + cow(T)_{ij} + \varepsilon_{ijklm},$$

where Y_{ijklm} = studied blood values on cow i in treatment j, on day of lactation m; μ = overall mean; T = fixed effect of treatment j (CON, BP); SD = sampling date during each experimental period (beginning, end); period = fixed effect of experimental period l (before and after change-over); DL = continuous effect of day of lactation m; T × SD = interaction between treatment j and sampling date k; cow(T) = random effect of cow i within treatment j; ε = random error. The effect of sequence of treatments was tested to evaluate any potential carry-over effect on blood variables. Because a carry-over effect was observed for GGT ($P < 0.001$), the experimental period 2 was excluded from analyses for this variable. For both models the following covariance structures were tested: unstructured (UN), variance components (VC), compound symmetry (CS), first order autoregressive [AR(1)], spatial power law [SP(POW)], spatial Gaussian [SP(GAU)], and spatial spherical [SP(SPH)]. As proposed by Littell et al. (1998), the one with the Bayesian information criterion closest to zero was selected. Results are presented as least squares means for treatment, the standard error of the mean and P-values for the effect of treatment. Differences between treatment groups were considered to be significant when $P < 0.05$.

RESULTS AND DISCUSSION

Feed Composition and Nutrient Intake

Due to differences in the original product and different processing procedures, nutritive values of by-products show high variations (Bocquier and González-García, 2010; Rosenfelder et al., 2013). As a result, the intend-

ed isocaloric and isonitrogenous formulation of the 2 concentrate mixtures could not quite be realized (Table 2). Net energy for lactation and CP content were 4 and 5% higher in the control group, respectively. However, with an average concentrate intake of less than 5 kg of DM per cow and day, these differences resulted only in a higher daily intake of less than 2 MJ of NE_L and 45 g of CP, which, in light of the total NE_L and CP intake, was only of minor relevance. This also applied to differences in uCP, where the BP diet showed a 3% higher content. Therefore, the minor differences in CP, uCP, and energy content of the concentrate mixtures did not result in remarkable differences in their intakes. The main differences between the 2 concentrate mixtures concerned different contents of the fiber fractions, as well as ether extract, starch, and crude ash. Starch content was markedly lower (−37%) in the BP mixture, whereas fractions of NDF, ADF, and ADL were 75, 75, and 139% higher, respectively. The ether extract content was more than doubled in the BP mixture (+137%).

The BP diet resulted in an increase in NDF, ADF, and ADL intake of 5.9, 4.5, and 5.7%, respectively (Table 3). Cows receiving BP also showed a higher ether extract intake (+28.2%), whereas the starch intake was lower (−33.8%) in these cows. Based on the different contents of these nutrients, this was to be expected. Dietary fat and fiber contents can influence DMI in dairy cattle, as shown in a review by Allen (2000). However, in this study, forage, concentrate, and total DMI were not affected by treatment. One explanation could be the fact that cows of this study were in a relatively late lactation stage, a period when DMI potential is stabilized and demands in energy and nutrients are decreased. It can also be that the differences in the composition of the concentrate mixtures for fiber and ether extract were too small to affect total DMI of the cows. In the present experiment, an average total DMI of 21.1 and 21.2 kg for BP and CON, respectively, was observed. This is slightly higher than findings published by Nousiainen et al. (2004) who summarized data from 50 milk production trials with 306 different diets based predominantly on grass silage, and found a total DMI of 19.8 kg. Due to lower concentrate supplementation in the current study, differences in forage DMI were even higher (16.3 compared with 11.6 kg). This can be explained by the higher average live weight of the cows and the high forage quality used, because these 2 factors strongly influence forage DMI (NRC, 2001). The high CP content of the forage mixture was the result of the inclusion of alfalfa hay, which had a CP content of 206 g/kg.

Milk Production and Concentrations of Physiological Blood Values

Milk production data and concentrations of physiological blood variables are shown in Table 4. The general level of milk production in this trial (26.0–27.8 kg) can be classified as above average when compared with other feeding trials for organic cows under similar conditions (Sehested et al., 2003; Baldinger et al., 2011). The substitution of a common concentrate for the BP mixture did not significantly affect milk yield or energy corrected milk yield. No effects on protein, fat, and lactose contents in milk or on somatic cell count were observed either. This is in agreement with Mowrey et al. (1999), who tested the effect of fibrous by-products as substitutes for grain and did not find differences in milk performance and milk composition when up to 50% of grain was replaced by fibrous by-products for mid-lactation dairy cows. Other studies

Table 3. Effect of concentrate mixture on daily intake of DM, nutrients, and energy

	Treatment[1]			
Item	CON	BP	SEM	*P*-value
DM (kg)				
Forage	16.3	16.3	0.4	0.979
Concentrate	4.7	4.8	0.2	0.627
Total DM	21.2	21.1	0.4	0.825
Nutrient (g)				
NDF	7,691	8,148	158	0.019
ADF	5,537	5,787	115	0.074
ADL	901	952	20	0.035
CP	3,709	3,647	67	0.436
uCP[2]	3,127	3,140	56	0.841
Ether extract	639	819	15	<0.001
Starch	2,439	1,615	145	0.002
Energy (MJ of NE_L)	140	138	3	0.440

[1]Mixtures: CON = control concentrate mixture; BP = by-product concentrate mixture.

[2]Utilizable CP at the duodenum (GfE, 2001).

Table 4. Effect of concentrate mixture on milk production traits and blood parameters

	Treatment[1]			
Item	CON	BP	SEM	*P*-value
Milk parameter				
Milk yield (kg/d)	26.0	27.8	1.4	0.354
ECM yield (kg/d)	26.9	27.7	1.0	0.579
Protein (g/kg)	33.5	33.2	0.4	0.513
Fat (g/kg)	43.8	42.7	1.0	0.433
Lactose (g/kg)	47.3	47.4	0.3	0.890
Urea (mg/100 mL)	21.6	18.4	0.8	0.013
Somatic cell counts ($\times 10^3$/mL)	122	133	23	0.758
Blood variable				
Aspartate aminotransferase (U/L)	66.5	70.2	4.6	0.573
BHBA (mmol/L)	0.67	0.69	0.03	0.623
Cholesterol (mg/100 mL)	180.3	201.7	9.6	0.126
Creatinine (mg/100 mL)	0.71	0.69	0.02	0.481
Gamma-glutamyl transferase (U/L)	27.2	19.6	1.4	<0.001
Glutamate dehydrogenase (U/L)	11.6	13.4	1.4	0.361
Glucose (mg/100 mL)	68.5	67.5	0.9	0.424
Urea (mg/100 mL)	27.1	24.7	0.8	0.038
Insulin (μIU/mL)	3.40	3.04	0.5	0.617
NEFA (mmol/L)	0.14	0.17	0.02	0.284
Haptoglobin (mg/mL)	5.69	3.58	2.02	0.468

[1]Mixtures: CON = control concentrate mixture; BP = by-product concentrate mixture.

also confirmed that starch from grains can be partly replaced by supplements with lower starch but higher fiber contents, without negative effects on animal performance (Bernard and McNeill, 1991; Ipharraguerre et al., 2002; Alamouti et al., 2009). In the current study, however, treatments differed not only in starch and fiber content, but also in fat content. Differences in chemical compositions resulted in a 180 g of higher fat intake for the BP group, resulting in an additional energy supply from dietary fat of almost 8 MJ of NE_L per day. It can therefore be assumed that the lower starch content in the BP diet was compensated by fat and digestible fiber as available energy sources, resulting in no observable differences in milk performance indicators. Milk urea content, as an indicator of adequate nitrogen and protein supply for ruminal microbes (Hof et al., 1997), was lower for cows fed the BP mixture (−3.2 mg/100 mL, $P = 0.013$). These differences can be explained by the higher CP content of the control mixture, because dietary CP content has been detected as the main nutritional factor influencing milk urea content (Nousiainen et al., 2004). The general level of milk urea observed in the current experiment (21.6 and 18.4 mg/100 mL) was within the desired range of 15 to 30 mg/100 mL, indicating an adequate protein and energy supply (Sawa et al., 2011) and in agreement with the findings of Baldinger et al. (2011), who observed milk urea contents of 18.5 and 19.9 mg/100 mL.

Most of the blood metabolites and haptoglobin were not affected by the concentrate type. However, similar to milk urea content, blood urea content was 2.4 mg/100 mL lower for cows receiving the BP mixture. Because a strong relationship exists between blood urea and milk urea concentration (Broderick and Clayton, 1997), this can also be explained by the higher CP content of the control diet. Gamma-glutamyl transferase concentration was 7.6 U/L higher for cows in the control group. According to González et al. (2011), increased levels of GGT can indicate liver damage. This can be the result of lesions that appear when more fat infiltrates the liver as a result of higher fat mobilization. However, it is unlikely that the control concentrate mixture would have had such negative effects on the liver health status and therefore the reasons for these differences remain unclear. Based on the GGT levels it cannot be concluded that cows receiving the control diet suffered from liver damage, because the observed 27.2 U/L are still within the 95% confidence interval for reference values for Holstein cows (Cozzi et al., 2011). González et al. (2011) also observed GGT levels of 28.9 and 30.6 U/L for cows with high and low lipomobilization, respectively.

Nutrient Balances, Efficiency of Milk Production, and Feed Versus Food Competition

Balances for energy and uCP depend on intake in relation to requirements (GfE, 2001). Because no major differences were present in nutrient intake and requirements for energy and uCP were similar, the treatment did not affect these balances (Table 5). The general level of energy (112–113%) and uCP (119–121%) balances are in agreement with the results of Baldinger

Table 5. Effect of concentrate mixture on nutrient balances, live weight change, and efficiency parameters

Item	Treatment[1]		SEM	*P*-value
	CON	BP		
NE_L balance[2] (%)	113	112	2	0.831
uCP balance[2] (%)	119	121	2	0.297
Live weight change (kg/d)	0.25	0.29	0.11	0.790
Nitrogen efficiency (milk N in % of N intake)	24.1	24.1	0.4	0.993
Feed conversion efficiency (kg of milk per kg of DMI)	1.28	1.28	0.02	0.998
eFCR[3] for energy (MJ/MJ of edible input)	1.39	5.55	0.19	<0.001
eFCR[3] for protein (g/g of edible input)	1.60	4.27	0.15	<0.001

[1]Mixtures: CON = control concentrate mixture; BP = by-product concentrate mixture.

[2]Calculated according to the methods of GfE (2001): (intake/requirements) × 100.

[3]eFCR = edible feed conversion ratio; defined as human-edible output in animal product per potentially human-edible feed input.

et al. (2011), who observed balances between 107 to 113% and 122 to 126%, respectively, under similar feeding conditions. Nitrogen efficiency, defined as the percentage of N in the milk compared with N intake, did not differ between the 2 groups (24.1%). This is in accordance with the results of Baldinger et al. (2011), who reported N efficiencies between 24.6 and 24.7% under similar feeding conditions. Powell et al. (2010), however, described a potential N efficiency between 30 and 35%. The reason for the lower N efficiency observed in our study is most likely the high CP content of the forage mixture compared with its energy content. This dietary constellation resulted in a positive ruminal N balance, leading to higher N losses. Several studies have reported that N efficiencies can be increased when dietary CP content is reduced (Broderick, 2003; Colmenero and Broderick, 2006). Live weight change did not significantly differ between groups and was similar to the findings of Agnew et al. (2003), reporting an average live weight gain of 0.23 kg per day over 12 different feeding trials. Feed conversion efficiency (kg of milk per kg of DMI) was also not affected by the concentrate supplementation, but compared with earlier studies, the observed feed conversion efficiency of 1.28 kg of milk per kg of DMI for both groups was somewhat low. The study by Khalili et al. (2002) reported feed efficiencies for organic dairy cows between 1.37 and 1.40 kg of milk per kg of DMI. A probable reason for the lower feed conversion efficiency in the current study is the fact that cows showed an average BW gain of 0.25 and 0.29 kg per day throughout the experiment, which is known to reduce feed conversion efficiency (Britt et al., 2003).

Feed conversion efficiency, however, affects mainly profitability and nutrient management and does not take the composition of the diet in terms of potentially human-edible inputs into consideration. Therefore, Wilkinson (2011) redefined efficiency and introduced the concept of an edible feed conversion ratio. According to his definition (human-edible input per human-edible output), values below 1 indicate that the livestock production system provides more edible energy or edible protein than it uses as feedstuff. For easier understanding, we suggested that values below 1 should indicate a negative food balance, and therefore, we defined eFCR as edible output per edible input. Similar calculations can be found in Oltjen and Beckett (1996) and CAST (1999). In the current study, the eFCR in the BP group (5.55) was almost 4 times higher than in the control group (1.39). When calculating eFCR for typical Californian conditions, Oltjen and Beckett (1996) reported a ratio of 1.28 for a corn silage and alfalfa hay-based ration and 0.57 for a least-cost ration, based on common feeds. Under common feeding strategies for the United Kingdom, Wilkinson (2011) estimated an eFCR of 2.13 for energy, and CAST (1999) reported ratios between 0.79 and 4.61 for different countries. This suggests that in the present study, the eFCR for energy in the control group was within the range of earlier studies, whereas the BP group distinctly improved eFCR for energy. The BP concentrate mixture also increased eFCR for protein (4.27 compared with 1.60), although differences between the treatment groups were smaller. The result for the control group was similar to the eFCR calculated by Wilkinson (2011; 1.41) and between the values reported by Oltjen and Beckett (1996) for 2 different diet formulations (0.96 and 2.76), whereas eFCR for the BP group was always higher. At first, it seems ambiguous that the control group eFCR for protein was higher than for energy, whereas in the BP group it was higher for energy than for protein. However, this can be explained by the soy cake in the BP mixture. For soy cake, an edible fraction of 0.8 was assumed, and soy cake is mainly a source of protein. Hence, the edible fraction for protein in the BP mixture was higher than for energy, which led to a lower eFCR for protein. Results of CAST (1999) also suggest that whether eFCR is higher for energy or for protein depends mainly on

the amount and type of concentrate supplements used. As a result, in their calculations for different countries, eFCR was sometimes higher for energy and sometimes it was higher for protein.

Unlike earlier studies, neither human-edible output from meat from culled cows, nor human-edible input for feeding dry cows and rearing were included in our calculations. However, Oltjen and Beckett's calculations (1996) suggest that this consideration would have influenced the results only marginally. The most critical point in calculating eFCR is the determination of the edible fractions of the different feedstuffs. This problem has been reported several times in combination with the food versus feed competition issue (Flachowsky, 2002; Wilkinson, 2011; Le Cotty and Dorin, 2012). Determination of the human edible fraction of feedstuffs is an approximate estimation, because no scientific concept has been developed yet and it strongly depends on the individual circumstances. During a hunger crisis, human-edible fractions would probably increase for all components that are somehow edible, whereas during times of surplus the willingness to consume, for example, fibrous by-products decreases. The edible fractions estimated in this paper can be regarded as feasible under current conditions in industrialized countries, without affecting human food habits. However, further research is needed to evaluate the amount of feed used not only for ruminants, but also for other livestock that could possibly support human nutrition. In addition, lactation studies are needed to evaluate long-term consequences of by-products feeding on the eFCR in dairy cows.

CONCLUSIONS

In this trial, the inclusion of a by-product mixture as a complete supplement for dairy cows instead of traditional cereals and pulses reduced human-edible inputs and increased eFCR up to 5.55 for energy and 4.27 for protein, without impairing milk production, health status, and feed conversion efficiency. Higher fat and fiber contents in the BP diet compensated for the lower starch content. Further studies, in particular with cows in early lactation and long-term studies, are needed to evaluate this feeding strategy.

ACKNOWLEDGMENTS

The authors thank the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, Bio Austria, the Salzburger Landesregierung, Raiffeisenverband Salzburg, and the Werner Lampert Beratungsges.m.b.H. for funding this research. Furthermore, we thank the Secondary Agriculture and Forestry College Ursprung for housing the experiment, the farm staff, especially Franz Grießner, for helping with the experimental work, as well as Lisa Baldinger and Karl Moder for statistical advice, Anita Dockner (Institute of Animal Nutrition and Functional Plant Compounds at University of Veterinary Medicine, Vienna) for performing haptoglobin analyses, and Kathleen Knaus for editing assistance.

REFERENCES

Agnew, R. E., T. Yan, J. J. Murphy, C. P. Ferris, and F. J. Gordon. 2003. Development of maintenance energy requirement and energetic efficiency for lactation from production data of dairy cows. Livest. Prod. Sci. 82:151–162.

Alamouti, A. A., M. Alikhani, G. R. Ghorbani, and Q. Zebeli. 2009. Effects of inclusion of neutral detergent soluble fibre sources in diets varying in forage particle size on feed intake, digestive processes, and performance of mid-lactation Holstein cows. Anim. Feed Sci. Technol. 154:9–23.

Allen, M. S. 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. J. Dairy Sci. 83:1598–1624.

Baldinger, L., R. Baumung, W. Zollitsch, and W. F. Knaus. 2011. Italian ryegrass silage in winter feeding of organic dairy cows: Forage intake, milk yield and composition. J. Sci. Food Agric. 91:435–442.

Bampidis, V. A., and P. H. Robinson. 2006. Citrus by-products as ruminant feeds: A review. Anim. Feed Sci. Technol. 128:175–217.

Bernard, J. K., and W. W. McNeill. 1991. Effect of high-fiber energy supplements on nutrient digestibility and milk-production of lactating dairy-cows. J. Dairy Sci. 74:991–995.

Bocquier, F., and E. González-García. 2010. Sustainability of ruminant agriculture in the new context: Feeding strategies and features of animal adaptability into the necessary holistic approach. Animal 4:1258–1273.

Bradford, G. E. 1999. Contributions of animal agriculture to meeting global human food demand. Livest. Prod. Sci. 59:95–112.

Britt, J. S., R. C. Thomas, N. C. Speer, and M. B. Hall. 2003. Efficiency of converting nutrient dry matter to milk in Holstein herds. J. Dairy Sci. 86:3796–3801.

Broderick, G. A. 2003. Effects of varying dietary protein and energy levels on the production of lactating dairy cows. J. Dairy Sci. 86:1370–1381.

Broderick, G. A., and M. K. Clayton. 1997. A statistical evaluation of animal and nutritional factors influencing concentrations of milk urea nitrogen. J. Dairy Sci. 80:2964–2971.

Cassidy, E. S., P. C. West, J. S. Gerber, and J. A. Foley. 2013. Redefining agricultural yields: From tonnes to people nourished per hectare. Environ. Res. Lett. 8:1–8.

Castle, M. E., M. S. Gill, and J. N. Watson. 1981. Silage and milk-production—A comparison between barley and dried sugar-beet pulp as silage supplements. Grass Forage Sci. 36:319–324.

Colmenero, J. J. O., and G. A. Broderick. 2006. Effect of dietary crude protein concentration on milk production and nitrogen utilization in lactating dairy cows. J. Dairy Sci. 89:1704–1712.

Council for Agricultural Science and Technology (CAST). 1999. Animal Agriculture and Global Food Supply. Task Force Report No. 135. Ames, IA.

Council for Agricultural Science and Technology (CAST). 2013. Animal Feed vs. Human food: Challenges and Opportunities in Sustaining Animal Agriculture Toward 2050. Issue Paper 53. Ames, IA.

Cozzi, G., L. Ravarotto, F. Gottardo, A. L. Stefani, B. Contiero, L. Moro, M. Brscic, and P. Dalvit. 2011. Short communication: Reference values for blood parameters in Holstein dairy cows: Effects of parity, stage of lactation, and season of production. J. Dairy Sci. 94:3895–3901.

Eastridge, M. L. 2006. Major advances in applied dairy cattle nutrition. J. Dairy Sci. 89:1311–1323.
Flachowsky, G. 2002. Efficiency of energy and nutrient use in the production of edible protein of animal origin. J. Appl. Anim. Res. 22:1–24.
GfE. 2001. Empfehlungen zur Energie- und Nährstoffversorgung der Milchkühe und Aufzuchtrinder. DLG-Verlag, Frankfurt am Main, Germany.
Gill, M. 2013. Converting feed into human food: The multiple dimensions of efficiency. Pages 1–14 in Proceedings of the FAO Symposium. H. P. S. Makkar and D. Beever, ed. FAO and Asian-Australasian Association of Animal Production Societies, Bangkok, Thailand.
Godfray, H. C., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin. 2010. Food security: The challenge of feeding 9 billion people. Science 327:812–818.
González, F. D., R. Muino, V. Pereira, R. Campos, and J. L. Benedito. 2011. Relationship among blood indicators of lipomobilization and hepatic function during early lactation in high-yielding dairy cows. J. Vet. Sci. 12:251–255.
Hof, G., M. D. Vervoorn, P. J. Lenaers, and S. Tamminga. 1997. Milk urea nitrogen as a tool to monitor the protein nutrition of dairy cows. J. Dairy Sci. 80:3333–3340.
Huhtanen, P. 1993. The effects of concentrate energy-source and protein-content on milk-production in cows given grass-silage ad-libitum. Grass Forage Sci. 48:347–355.
Huhtanen, P., S. Jaakkola, and E. Saarisalo. 1995. The effects of concentrate energy-source on the milk-production of dairy-cows given a grass silage-based diet. Anim. Sci. 60:31–40.
Ipharraguerre, I. R., R. R. Ipharraguerre, and J. H. Clark. 2002. Performance of lactating dairy cows fed varying amounts of soyhulls as a replacement for corn grain. J. Dairy Sci. 85:2905–2912.
Khalili, H., E. Kuusela, M. Suvitie, and P. Huhtanen. 2002. Effect of protein and energy supplements on milk production in organic farming. Anim. Feed Sci. Technol. 98:103–119.
Knaus, W. 2009. Dairy cows trapped between performance demands and adaptability. J. Sci. Food Agric. 89:1107–1114, 1163.
Knaus, W. 2013. Re-thinking dairy cow feeding in light of food security. AgroLife Scientific J. 2:36–40.
Le Cotty, T., and B. Dorin. 2012. A global foresight on food crop needs for livestock. Animal 6:1528–1536.
Littell, R. C., P. R. Henry, and C. B. Ammerman. 1998. Statistical analysis of repeated measures data using SAS procedures. J. Anim. Sci. 76:1216–1231.
Mowrey, A., M. R. Ellersieck, and J. N. Spain. 1999. Effect of fibrous by-products on production and ruminal fermentation in lactating dairy cows. J. Dairy Sci. 82:2709–2715.
Nousiainen, J., K. J. Shingfield, and P. Huhtanen. 2004. Evaluation of milk urea nitrogen as a diagnostic of protein feeding. J. Dairy Sci. 87:386–398.
NRC. 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed. Natl. Acad. Press, Washington, DC.
Oltjen, J. W., and J. L. Beckett. 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74:1406–1409.
Phipps, R. H., J. D. Sutton, R. F. Weller, and J. A. Bines. 1987. The effect of concentrate composition and method of silage feeding on intake and performance of lactating dairy-cows. J. Agric. Sci. 109:337–343.
Powell, J. M., C. J. P. Gourley, C. A. Rotz, and D. M. Weaver. 2010. Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. Environ. Sci. Policy 13:217–228.
Rosenfelder, P., M. Eklund, and R. Mosenthin. 2013. Nutritive value of wheat and wheat by-products in pig nutrition: A review. Anim. Feed Sci. Technol. 185:107–125.
SAS Institute Inc. 2009. SAS/STAT 9.2. User's Guide. SAS Inst. Inc., Cary, NC.
Sawa, A., M. Bogucki, and S. Krezel-Czopek. 2011. Effect of some factors on relationships between milk urea levels and cow fertility. Arch. Tierzucht 54:468–476.
Sehested, J., T. Kristensen, and K. Soegaard. 2003. Effect of concentrate supplementation level on production, health and efficiency in an organic dairy herd. Livest. Prod. Sci. 80:153–165.
Thomas, C., K. Aston, S. R. Daley, and J. Bass. 1986. Milk-production from silage 4. The effect of the composition of the supplement. Anim. Prod. 42:315–325.
Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. USA 108:20260–20264.
VDLUFA. 1993. Handbuch der Landwirtschaftlichen Versuchs- und Untersuchungsmethodik (VDLUFA-Methodenbuch), Bd. III: Die Chemische Untersuchung von Futtermitteln. VDLUFA-Verlag, Darmstadt, Germany.
Wilkinson, J. M. 2011. Re-defining efficiency of feed use by livestock. Animal 5:1014–1022.
Zebeli, Q., S. Sivaraman, S. M. Dunn, and B. N. Ametaj. 2011. Intermittent parenteral administration of endotoxin triggers metabolic and immunological alterations typically associated with displaced abomasum and retained placenta in periparturient dairy cows. J. Dairy Sci. 94:4968–4983.