



Effects of malic acid on microbial efficiency and metabolism in continuous culture of rumen contents and on performance of mid-lactation dairy cows

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Abstract

Two experiments were conducted to determine the effect of malic acid supplementation on: (1) nutrient digestibility and metabolism of ruminal microorganisms in continuous culture of rumen contents and (2) lactation performance of mid-lactation dairy cows and total tract nutrient digestibility. In experiment 1, digestibility of acid detergent fiber (ADF) and neutral detergent fiber (aNDF) was higher ($P < 0.05$) when malic acid was supplemented at 100 g per cow per day compared to 0 g per cow per day; 50 g per cow per day supplemental malic acid was intermediate. Malic acid supplementation did not affect ($P > 0.05$) the production of total volatile fatty acids, propionic acid, butyric acid, and isobutyric acid, the ratio of acetic to propionic acid, or pH. Microbial nitrogen (N) production and efficiency of organic matter (OM) and total carbohydrate use for microbial N production increased ($P < 0.05$) with either 50 or 100 g of supplemental malic acid. Based on the *in vitro* results, it appeared that 50 g supplemental malic acid per cow per day would be effective *in vivo* in altering ruminal

Abbreviations: ADF, acid detergent fiber; BCS, body condition score; BW, body weight; CP, crude protein; CPM, Cornell–Penn–Miner; DM, dry matter; NDF, neutral detergent fiber; N, nitrogen; NFC, nonfiber carbohydrate; NSC, nonstructural carbohydrate; OM, organic matter; VFA, volatile fatty acids

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fermentation and microbial efficiency. In experiment 2, milk yield was higher ($P < 0.05$) for cows fed supplemental malic acid at a calculated amount of 50 g per cow per day. There was no effect ($P > 0.05$) of malic acid supplementation on content of fat, true protein, or lactose in milk. However, yield of true protein and lactose was higher ($P < 0.05$) for cows fed supplemental malic acid because of higher milk yield. Total tract digestibility of dry matter (DM), OM, crude protein (CP), ADF, aNDF, hemicellulose, cellulose, ether extract, starch, and nonfiber carbohydrate (NFC) was not affected ($P > 0.05$) by malic acid supplementation. In conclusion, malic acid supplementation in lactating cow diets was effective at increasing microbial N production and microbial efficiency measured in vitro and milk yield.

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1. Introduction

Malic acid is a four-carbon dicarboxylic acid that is an intermediate in the succinate–propionate pathway of ruminal bacteria (Castillo et al., 2004). In vitro, malic acid has stimulated lactate utilization (Nisbet and Martin, 1991), increased concentrations of propionate and total volatile fatty acids (VFA; Martin and Streeter, 1995; Carro and Ranilla, 2003), increased pH (Martin and Streeter, 1995; Carro and Ranilla, 2003), decreased methane production (Carro and Ranilla, 2003), decreased lactate concentration (Carro and Ranilla, 2003), and increased digestibility of dry matter (DM; Carro et al., 1999; Chairatanayuth, 1981), organic matter (OM; Carro et al., 1999), neutral detergent fiber (NDF; Carro et al., 1999), and hemicellulose (Carro et al., 1999). Recently, malic acid has been suggested as a substitute for monensin in beef cattle diets because malic acid has effects on ruminal fermentation analogous to ionophores (Castillo et al., 2004). However, the mode of action for malic acid is different than ionophores (Castillo et al., 2004). Malic acid stimulates succinate and (or) propionate production by *Selenomonas ruminantium*, thereby decreasing the availability of H_2 to methanogenic bacteria (Castillo et al., 2004).

Although in vitro studies have shown positive effects of malic acid on ruminal fermentation, there are limited in vivo studies available to evaluate the effects of malic acid on dairy cow performance. Alferez (1978) fed early lactation Holstein cows an alfalfa hay, corn silage, and steam-rolled barley-based diet that was supplemented with malic acid (0, 70, 105, or 140 g supplemental malic acid per cow per day). Cows fed 105 g of malic acid had higher milk yield, fat-corrected milk yield, and fat yield and were more efficient in converting DM into milk than cows fed 0 or 70 g malic acid. Feeding malic acid above 105 g did not increase productivity or feed efficiency. Stallcup (1979) fed Holstein cows a sorghum-sudan forage and corn grain-based diet with 0, 28, or 70 g supplemental malic acid per cow per day. Cows fed 70 g of malic acid had higher milk yield than cows fed 0 g malic acid. In a second trial (Stallcup, 1979), cows fed an alfalfa-grass hay and sorghum silage-based diet with 100 g supplemental malic acid had higher solids-corrected milk and milk fat content than cows fed the diet with no supplemental malic acid. Kung et al. (1982) found that early and mid-lactation Holstein cows fed a corn silage-based diet with 140 g of supplemental malic acid per day had greater persistency of milk production than cows fed 0, 70, or 105 g of malic acid per day. Total ruminal VFA concentration was increased with

malic acid supplementation compared to the control diet. Dry matter intake, milk yield, and milk composition did not differ among malic acid treatments.

More recently, Vicini et al. (2003) observed no difference in milk yield between cows fed a corn-based control diet or the control diet supplemented with a commercial product containing soluble sugars and malic acid (estimated 4 g malic acid per cow per day). Martin et al. (2000) previously determined that the malic acid concentration in the commercial product was not high enough to stimulate lactate utilization by *Selenomonas ruminantium*, a predominant ruminal microorganism that utilizes lactic acid.

In a preliminary report, Devant and Bach (2004) found that early lactation cows fed a diet containing 84 g supplemental malate compared to cows fed a control diet had increased milk yield during peak lactation, consumed more concentrate, but had similar ruminal pH. Devant and Bach (2004) suggested that malate might be effective in preventing ruminal acidosis.

Clearly, the results of the few lactation studies conducted with malic acid supplementation in dairy cows are contradictory. Across the reported studies, there was a wide range in supplementation level of malic acid. In addition, Castillo et al. (2004) suggested that dietary factors, such as forage to concentrate ratio and forage type, are important in determining responses to malic acid supplementation because the content of malic acid in the basal diet will vary. The malic acid content of forage varies with forage type (legumes > grasses), forage variety, maturity (immature > mature), and processing (fresh > hay or pelleting; Callaway et al., 1997). In a study with dairy goats (Salama et al., 2002), supplementation with yeast and malic acid was not beneficial for lactation performance because of the high concentration of malic acid in the forages (high proportion of alfalfa) in the basal diet.

It is unclear what the ideal dosage of malic acid is for lactating cows fed corn-based diets. The objective of experiment 1 was to determine nutrient digestibility and metabolism of ruminal microorganisms in continuous culture when fed a control diet or a control diet supplemented to provide 50 or 100 g malic acid per cow per day. The objective of experiment 2 was to determine the effect of feeding malic acid at a rate of 50 g malic acid per cow per day (determined from experiment 1) on the lactation performance of mid-lactation dairy cows and on total tract nutrient digestibility.

2. Materials and methods

2.1. Experiment 1: continuous culture study

2.1.1. Diets

The basal diet was formulated using the CPM Dairy[®] nutrition model (version 2.0; Cornell–Penn–Miner, Cornell University, Ithaca, NY, USA) for a lactating cow eating 26.4 kg DM and producing 45 kg of milk per day. Ingredient composition of the basal diet was approximately 351 g of corn silage, 170 g alfalfa-grass silage, and 479 g supplement per kg diet on a DM basis (Table 1). DL-Malic acid (998 g/kg; Harcros Chemicals Inc., Kansas City, KS, USA) was added to the basal diet to provide 0, 50, or 100 g of supplemental malic acid per cow per day. The diets were mixed at the Rumen Fermentation Profiling Lab (West Virginia University, Morgantown, WV, USA). Ingredient and chemical composition

Table 1

Ingredient and chemical composition [dry matter (DM) basis] of diets supplemented with 0, 50, or 100 g malic acid per cow per day that were fermented in a continuous culture system (experiment 1)

	Supplemental malic acid (g per cow per day)		
	0	50	100
Ingredient composition (g/kg DM)			
Corn silage	351.2	350.5	349.9
Alfalfa-grass silage	169.9	169.6	169.3
Ground corn	170.3	170.0	169.7
Soybean meal 44	218.6	218.2	217.8
Beet pulp	65.8	65.7	65.5
Soybean hulls	4.1	4.1	4.1
Sodium bicarbonate	7.2	7.2	7.2
Dicalcium phosphate	3.6	3.6	3.6
Sodium chloride	2.9	2.9	2.9
Calcium carbonate	1.8	1.8	1.8
Megalac ^a	1.9	1.9	1.9
Dynamate ^b	1.1	1.1	1.1
Mepron ^c	0.6	0.6	0.6
Vitamin E ^d	0.4	0.4	0.4
Selenium ^e	0.3	0.3	0.3
Beacon trace mineral mix ^f	0.1	0.1	0.1
854 Dairy 5 × mineral and vitamin mix ^g	0.1	0.1	0.1
Malic acid	–	1.9	3.8
Chemical composition (g/kg DM)			
Crude protein	182	182	183
Soluble protein	44	42	43
Neutral detergent fiber	313	318	322
Acid detergent fiber	202	214	215
Nonstructural carbohydrate	347	335	336
Starch	306	294	295
Sugar	41	41	41
Ether extract	23	27	27
Ash	62	64	65
Nonfiber carbohydrate ^h	419	409	403

^a Church & Dwight Co., Inc., Princeton, NJ, USA.

^b IMC, Lake Forest, IL, USA.

^c Degussa Corporation Feed Additives, Kennesaw, GA, USA.

^d Contained 44,100 KIU/kg.

^e Contained 606 mg/kg.

^f Contained 71 g Ca/kg, 1.9 g Mg/kg, 79 g S/kg, 10,714 mg Fe/kg, 214,285 mg Zn/kg, 41,326 mg Cu/kg, 107,142 mg Mn/kg, 841 mg Se/kg, 2448 mg Co/kg, and 2040 mg I/kg.

^g Contained 98.6 g Ca/kg, 0.6 g P/kg, 10.5 g Mg/kg, 13.3 g K/kg, 0.4 g S/kg, 5.3 g Na/kg, 0.8 g Cl/kg, 35,946 KIU vitamin A/kg, 12,247 KIU vitamin D/kg, and 44,535 IU vitamin E/kg.

^h Nonfiber carbohydrate = 1000 – (CP + NDF + ether extract + ash).

(DM basis) of the diets were similar (Table 1). Chemical analyses of diets were conducted according to the procedures of Miller-Webster et al. (2002) (Section 2.1.3). Silages were sent to a commercial laboratory (Dairy One, Ithaca, NY, USA) for wet chemistry analysis (Section 2.1.3; Table 2).

Table 2

Chemical composition and fermentation analysis [dry matter (DM) basis] of corn silage and alfalfa-grass silage (experiment 1)

	Corn silage	Alfalfa-grass silage
Composition (g/kg DM)		
Dry matter	323	324
Net energy for lactation (MJ/kg DM)	6.8	5.4
Crude protein	71	183
Soluble protein	31	121
Acid detergent insoluble crude protein	4	12
Neutral detergent insoluble crude protein	11	27
Acid detergent fiber	244	365
Neutral detergent fiber	417	495
Nonfiber carbohydrate	457	211
Nonstructural carbohydrate	396	69
Starch	353	8
Sugar	43	61
Lignin	33	68
Ether extract	31	38
Ash	35	100
Calcium	2.6	10.6
Phosphorus	1.7	3.0
Sulfur	0.7	1.9
Magnesium	1.8	2.1
Potassium	6.2	26.6
Sodium	0.04	0.18
Chloride	1.5	6.8
Composition (mg/kg DM)		
Iron	96	292
Zinc	17	26
Copper	6	9
Manganese	21	41
Molybdenum	1	1.6
Fermentation analysis (g/100 g DM)		
Acetic acid		2.62
Propionic acid		0.12
Butyric acid		0.03
Lactic acid		8.00
Total acids		10.83
Ammonia		1.49
pH		4.3

2.1.2. Continuous culture system

The experiment was performed at the Rumen Fermentation Profiling Lab (West Virginia University, Morgantown, WV, USA). A continuous culture system similar to that described by Hoover et al. (1976) was used. Each fermenter had a working volume of 1164 ml. Approximately 3 h after feeding, ruminal inoculum for the fermenters was obtained from two ruminally cannulated, lactating Holstein cows consuming a total mixed ration ad libitum (230 g corn silage, 110 g mixed grass silage, 100 g alfalfa hay, and 560 g concentrate per

kg DM). Ruminal fluid was pooled before inoculating fermenters. The fermentation period was 9 days. All diets were fermented in triplicate under the following conditions: liquid dilution rate: 0.13/h, solids dilution rate: 0.0455/h, solids retention time: 22 h, fermentation temperature: 39 °C, and feed intake: 100 g DM per day. The artificial saliva of [Weller and Pilgrim \(1974\)](#) was infused continuously at a rate to provide the 0.13/h liquid flow. Diets were fed automatically four times daily at 6-h intervals. Fermenter pH was monitored at 2-h intervals.

During the last 3 days of the fermentation period, the effluents were collected in an ice bath and a 1 L sample was composited, and saved for analyses (Section 2.1.3). After the effluent was collected on day 9, the contents of the fermenters were allowed to settle and the upper fluid layer was used for collection of microbes ([Miller-Webster et al., 2002](#)). Briefly, two samples (250 ml) were taken from each fermenter and centrifuged for 20 min at $200 \times g$. The supernatants were centrifuged for 15 min at $30,000 \times g$, the pellets combined, resuspended in saline and again centrifuged for 15 min at $30,000 \times g$. The supernatants were discarded and the pellets were resuspended in 20 ml of a 50:50 mixture of distilled water and methanol, and centrifuged for 15 min at $30,000 \times g$. The supernatants were poured off and the pellets resuspended in distilled water and lyophilized.

2.1.3. Chemical analyses

Chemical analyses of diets, effluent, and microbes were conducted according to the procedures of [Miller-Webster et al. \(2002\)](#). Samples were analyzed for DM (method 930.15; [AOAC, 1995](#)), ash (method 942.05; [AOAC, 1995](#)), ether extract (method 920.39; [AOAC, 1995](#)), aNDF ([Van Soest et al., 1991](#)), and ADF (method 973.18; [AOAC, 1995](#)). The aNDF was determined using sodium sulfite and heat stable amylase and both aNDF and ADF were inclusive of residual ash. Total nitrogen (N) in diets, effluents, bacterial and ammonia was determined using an automated Tecator digestion system (Tecator, Inc., Herndon, VA, USA; method 976.05; [AOAC, 1995](#)). Crude protein (CP) was determined by the method of [Krishnamoorthy et al. \(1982\)](#). Nonstructural carbohydrate (NSC), sugars and starches were determined by the procedure of [Smith \(1969\)](#), except that ferricyanide was used to detect reducing sugars. Analysis of VFA was performed with a gas chromatographic separation procedure (Supelco Bulletin 749E; Supelco, Inc. Bellefonte, PA, USA) using a gas chromatograph (Varian 3300; Varian, Inc., Palo Alto, CA, USA) equipped with a FID detector and a 2 m \times 2 mm glass column packed with 10% SP-1200/1% H₃PO₄ on 80/100 chromosorb WAW (Supelco, Inc. Bellefonte, PA, USA). Effluent DM was determined by centrifuging a 34–40 g sample of effluent at $30,000 \times g$ for 45 min. The supernatant was discarded and the particulate matter was dried at 110 °C for 24 h and reweighed. The adaptations of the aNDF and ADF analyses for continuous culture effluents were described by [Crawford et al. \(1983\)](#). Effluent and bacterial content of purines were determined by the procedure of [Zinn and Owens \(1986\)](#). Digestion coefficients for DM, OM, aNDF, ADF and CP, and total flows of non-ammonia microbial and dietary N were calculated as described by [Stern and Hoover \(1990\)](#).

Silage samples were analyzed at a commercial laboratory (Dairy One, Ithaca, NY, USA) for DM (method 930.15), CP (method 990.03), and ash (method 942.05) according to [AOAC \(2000\)](#) methods. Soluble protein was determined with a sodium borate, sodium phosphate buffer procedure ([Roe and Sniffen, 1990](#)). Nonstructural carbohydrate and sugar

were determined by the procedures of Hall et al. (1999) and Smith (1969) where ferricyanide was used to detect reducing sugars. Starch was determined with a YSI 2700 SELECT biochemistry analyzer (Application note 319; YSI Incorporated, Yellow Springs, OH, USA). Acid detergent fiber with residual ash, aNDF with residual ash (using α -amylase and sodium sulfite), and acid detergent lignin were determined by the ANKOM A200 filter bag technique (ANKOM Technology Corp., Fairport, NY, USA) (Van Soest et al., 1991). Neutral detergent insoluble CP and acid detergent insoluble CP were determined by analyzing aNDF and ADF residues for Kjeldahl N (Licitra et al., 1996). Ether extract was measured using the automated Tecator Soxtec System HT6 (Application note AN 301; FOSS North America, Eden Prairie, MN, USA). Calcium, phosphorous, magnesium, potassium, sodium, iron, zinc, copper, manganese, and molybdenum were measured using a Thermo Jarrell Ash IRIS Advantage Inductively Coupled Plasma Radial Spectrometer (model ICAP 61; Thermo Jarrell Ash, Ithaca, NY, USA) (Sirois et al., 1994). Sulfur was measured using an elemental analyzer (Application note form 203-601-229, 08/92; model SC-432; LECO Corporation, St. Joseph, MI, USA) (Sirois et al., 1994). The chloride ion was measured using a potentiometric titrator (Application bulletin 130; Brinkmann Metrohm 716 Titrino titration unit with silver electrode; Brinkmann Instruments, Inc., Westbury, NY, USA). Nonfiber carbohydrate (NFC) was calculated as the difference between 100 and the sum of CP, aNDF, ether extract, and ash. Analysis of VFA was performed with a gas chromatographic separation procedure (Supelco Bulletin 749E; Supelco, Inc. Bellefonte, PA, USA).

2.1.4. Statistical analyses

Data were analyzed as a completely randomized design using the general linear model (GLM) procedure of Statistical Analysis Systems (SAS; version 8.02, Statistical Analysis Systems Institute Inc., Cary, NC, USA). The model used was: $Y_{ij} = \mu + T_i + e_{ij}$ where μ is the overall mean, T_i is the effect of treatment ($i = 1-3$), and e_{ij} is the residual. Treatment effects were considered different based on a significant ($P < 0.05$) F ratio. Treatment means were separated using Duncan's multiple range test at the 5% level of probability. Least squares means were reported.

2.2. Experiment 2: production study

2.2.1. Cows and diets

Forty Holstein cows with average days in milk of 158 ± 48 , body weight (BW) of 644 ± 83 kg, and body condition score (BCS) of 3.09 ± 0.32 were assigned randomly to one of two treatments: a diet that contained 0 g of supplemental malic acid (998 g/kg DL-malic acid; Harcros Chemicals Inc., Kansas City, KS, USA) per cow per day (control) or a diet that contained 50 g of supplemental malic acid per cow per day (malic acid). The 50 g of supplemental malic acid per cow per day was projected from a cow eating 25.4 kg of a diet containing 2.0 g malic acid/kg. Based on the *in vitro* results, it appeared that 50 g supplemental malic acid per cow per day would be effective *in vivo* at altering ruminal fermentation and efficiency. The diets were formulated using the CPM Dairy[®] nutrition model (version 2.0; Cornell-Penn-Miner, Cornell University, Ithaca, NY, USA). The diets were formulated for a cow 150 days in milk with a BCS of 3.10, a BW of 645 kg, a DM intake of 25.4 kg per day, and a milk yield of 40.9 kg per day containing 35 g/kg fat and

30 g/kg protein. The ingredient composition (Table 3), chemical composition (Table 4), and particle size (Table 5) of the diets were similar. Silage quality was typical of the Northern New York region (Table 6).

Cows were housed in two pens in a free-stall barn for the duration of the experiment. The pens were the same size with similar animal density, bunk space, stall design, flooring, and water accessibility. Cows were group-fed by treatment for ad libitum intake (approximately $1.05 \times$ expected intake) once daily at 0900 h. The diets were fed as total mixed rations. Dry matter intake was estimated daily based on feed offered and refused and number of cows in each group. Cows were milked twice per day in a double-six herringbone milking parlor at 0600 and 1800 h.

The experimental design was a crossover design with two 28-day periods. Samples and data were collected during the last 7 days of each period.

2.2.2. *Sampling and chemical analyses*

Forages were sampled weekly and dried at 105 °C overnight to determine DM content. Diets were adjusted weekly to reflect changes in forage DM content. During four consecutive days during the last week of each period, diets and orts were sampled and DM content determined for use in estimating group intake of cows in each pen. The remaining samples of diets from each day (4 days total) were composited by diet. A portion of each diet composite was used to determine particle size distribution (Lammers et al., 1996) and another portion of each diet composite was submitted to a commercial laboratory (Dairy One, Ithaca, NY, USA) for wet chemistry analysis and analyzed as described previously (Section 2.1.3). Malic acid in the diets was quantified by high performance liquid chromatography (method 986.13, AOAC, 2000; The National Food Laboratory, Inc., Dublin, CA, USA).

Body weight and BCS (Wildman et al., 1982) were determined for each cow at the beginning and end of each period. Dry matter intake of each pen and milk yield of each cow were measured daily during the last week of each period. Milk was sampled from each cow at consecutive morning and evening milkings on 1 day during the last week of each period. The milk samples were analyzed at a commercial laboratory (Dairy One, Ithaca, NY, USA) for fat, protein, lactose, milk urea N and somatic cells by infrared procedures (Foss 4000; Foss Technology, Eden Prairie, MN, USA). Average fat and protein yields were calculated by multiplying milk yield by fat and protein content on an individual cow basis.

Total tract digestibility of DM, OM, CP, ADF, aNDF, hemicellulose, cellulose, ether extract, starch, and NFC was determined using five cows per treatment during the last week of each period. Diets were mixed to contain 1 g chromic oxide/kg DM as an indigestible marker. During four consecutive days during the last week of each period, samples of diets and orts were collected daily and grab samples of feces were collected twice daily (0800 and 1600 h). Fecal samples from each cow were composited by combining approximately 100 g of feces from each time point. Samples of diets, orts, and feces were frozen at -20°C until analysis.

Diets and fecal samples were analyzed for DM, ash, CP, NFC, starch, ADF, aNDF, and lignin (Dairy One, Ithaca, NY, USA; Section 2.1.3). Diets and fecal samples were analyzed for chromic oxide according to the procedures of Dansky and Hill (1952) and Brisson (1956) at the University of Georgia Poultry Research Laboratory (Athens, GA, USA). Total tract

Table 3

Ingredient composition (dry matter basis) of a diet containing no supplemental malic acid (control) or a diet supplemented to provide 50 g malic acid per cow per day (malic acid) (experiment 2)

	Period 1 diet				Period 2 diet			
	Control		Malic acid		Control		Malic acid	
	(kg/day)	(g/kg)	(kg/day)	(g/kg)	(kg/day)	(g/kg)	(kg/day)	(g/kg)
Corn silage	8.04	325.1	8.04	325.1	7.56	298.3	7.56	298.2
Alfalfa-grass silage								
1st cut	1.88	76.0	1.88	75.9	2.34	92.3	2.34	92.3
3rd cut	2.22	89.8	2.22	89.8	–	–	–	–
4th cut	–	–	–	–	2.87	113.0	2.87	113.0
Ground corn	4.19	169.4	4.19	169.3	4.19	165.3	4.19	165.3
Whole cotton seed	1.25	50.6	1.25	50.6	1.25	49.4	1.25	49.4
Sugar beet pulp	1.03	41.7	1.03	41.7	1.24	48.8	1.24	48.8
Megalac-R ^{®a}	0.43	17.6	0.43	17.6	0.22	8.6	0.22	8.6
Sugar cane molasses	0.34	13.6	0.34	13.6	0.34	13.3	0.34	13.3
Sodium bicarbonate	0.20	8.1	0.20	8.1	0.20	7.9	0.20	7.9
Concentrate mix								
Soybean meal 48	1.71	69.2	1.68	68.0	1.71	67.5	1.68	66.4
Canola meal	1.61	65.2	1.60	64.5	1.61	63.6	1.60	63.0
Wheat middlings	0.68	27.3	0.68	27.3	0.68	26.7	0.68	26.7
Soy Pass ^{®b}	0.40	16.3	0.40	16.3	0.40	15.9	0.40	15.9
Calcium carbonate	0.22	8.8	0.22	8.8	0.22	8.6	0.22	8.6
Corn gluten meal	0.20	8.1	0.20	8.1	0.20	7.9	0.20	7.9
Soybean hulls	0.13	5.2	0.13	5.2	0.13	5.1	0.13	5.1
Sodium chloride	0.08	3.1	0.08	3.1	0.08	3.1	0.08	3.1
Magnesium oxide	0.04	1.5	0.04	1.5	0.04	1.4	0.04	1.4
Dynamate ^{®c}	0.02	0.7	0.02	0.7	0.02	0.7	0.02	0.7
Vitamin E ^d	0.01	0.5	0.01	0.5	0.01	0.5	0.01	0.5
Selenium ^e	0.008	0.3	0.008	0.3	0.008	0.3	0.008	0.3
Alimet ^{®f}	0.008	0.3	0.008	0.3	0.008	0.3	0.008	0.3
Trace mineral mix ^g	0.008	0.3	0.008	0.3	0.008	0.3	0.008	0.3
Mineral mix ^h	0.004	0.2	0.004	0.2	0.004	0.2	0.004	0.2
Mineral and vitamin mix ⁱ	0.004	0.2	0.004	0.2	0.004	0.2	0.004	0.2
Malic acid ^j	–	–	0.05	2.0	–	–	0.05	2.0
Chromic oxide ^k	0.024	1.0	0.024	1.0	0.024	0.9	0.024	0.9

^a Church & Dwight Co., Inc., Princeton, NJ, USA.

^b Lingo Tech USA, Inc., Rothschild, WI, USA.

^c IMC, Lake Forest, IL, USA.

^d Contained 44,100 KIU/kg.

^e Contained 606 mg/kg.

^f Novus International, Inc., St. Louis, MO, USA.

^g Contained 10 g Ca/kg, 88 g S/kg, 4102 mg Fe/kg, 102,044 mg Zn/kg, 20,425 mg Cu/kg, 81681 mg Mn/kg, 775 mg Co/kg, and 1419 mg I/kg.

^h Contained 71 g Ca/kg, 1.9 g Mg/kg, 79 g S/kg, 10,714 mg Fe/kg, 214,285 mg Zn/kg, 41,326 mg Cu/kg, 107,142 mg Mn/kg, 841 mg Se/kg, 2448 mg Co/kg, and 2040 mg I/kg.

ⁱ Contained 98.6 g Ca/kg, 0.6 g P/kg, 10.5 g Mg/kg, 13.3 g K/kg, 0.4 g S/kg, 5.3 g Na/kg, 0.8 g Cl/kg, 35,946 KIU vitamin A/kg, 12,247 KIU vitamin D/kg, and 44,535 IU vitamin E/kg.

^j 998 g/kg DL-malic acid; Harcros Chemicals Inc., Kansas City, KS, USA.

^k Chromic oxide was fed during the last 7 days of each period and comprised 1 g/kg of the total DM fed (24 g per cow per day).

Table 4

Chemical composition [dry matter (DM) basis] of a diet containing no supplemental malic acid (control) or a diet supplemented to provide 50 g malic acid per cow per day (malic acid) (experiment 2)

	Period 1 diet		Period 2 diet	
	Control	Malic acid	Control	Malic acid
Composition (g/kg DM)				
Dry matter	476	473	478	486
Net energy for lactation ^a (MJ/kg DM)	6.9	6.9	6.7	6.8
Crude protein	169	166	188	188
Soluble protein	63	66	73	60
Acid detergent insoluble crude protein	8	9	9	8
Neutral detergent insoluble crude protein	45	34	37	38
Acid detergent fiber	202	226	217	217
aNeutral detergent fiber	335	342	329	347
peNDF ^b	223	223	218	218
Nonfiber carbohydrate	426	403	400	387
Nonstructural carbohydrate	315	311	302	317
Starch	265	258	232	257
Sugar	50	53	70	60
Lignin	44	45	49	48
Ether extract	42	47	40	41
Ash	73	76	79	75
Calcium	8.6	8.0	7.6	7.3
Phosphorus	4.3	3.7	3.9	3.4
Sulfur	2.0	2.3	2.3	2.4
Magnesium	3.2	2.9	3.0	2.8
Potassium	14.3	13.5	14.0	12.3
Sodium	3.5	2.9	3.7	2.5
Chloride	4.1	3.6	6.2	5.2
Malic acid	5.88	7.57	7.20	8.14
Composition (mg/kg DM)				
Iron	156	149	156	130
Zinc	83	91	69	50
Copper	15	14	12	8
Manganese	55	55	55	40
Molybdenum	0.8	0.9	0.6	0.6

^a Net energy for lactation was calculated by Dairy One (Ithaca, NY, USA) using National Research Council (2001) equations.

^b Physically effective NDF; determined using CPM Dairy[®] nutrition model.

Table 5

Particle size distribution of a diet containing no supplemental malic acid (control) or a diet supplemented to provide 50 g malic acid per cow per day (malic acid) (experiment 2)

Particle size	Period 1 diet		Period 2 diet	
	Control	Malic acid	Control	Malic acid
	g/kg as fed retained			
>19.0 mm (top)	107	112	122	127
8.0–19 mm (middle)	426	438	442	442
<8.0 mm (bottom)	467	450	436	431

Table 6

Chemical composition and fermentation analysis [dry matter (DM) basis] of corn silage and alfalfa-grass silage (AGS) fed during period 1 (P1) and period 2 (P2) (experiment 2)

	Corn silage		AGS (1st cut)		AGS (3rd cut)	AGS (4th cut)
	P1	P2	P1	P2	P1	P2
Composition (g/kg DM)						
Dry matter	362	379	259	295	377	383
Net energy for lactation (MJ/kg DM)	7.0	7.3	5.9	6.2	6.0	5.7
Crude protein	78	74	208	192	202	209
Soluble protein	49	44	154	125	123	115
Acid detergent insoluble crude protein	11	6	10	9	14	13
Neutral detergent insoluble crude protein	17	8	28	26	21	34
Acid detergent fiber	254	213	327	317	347	321
Neutral detergent fiber	414	364	503	519	471	474
Nonfiber carbohydrate	449	493	160	165	190	197
Nonstructural carbohydrate	393	416	52	72	94	93
Starch	365	394	5	31	49	9
Sugar	28	22	47	41	45	84
Lignin	27	27	42	34	55	75
Ether extract	37	37	50	59	58	54
Ash	40	39	106	92	100	100
Calcium	3.0	2.7	7.1	4.6	8.8	12.8
Phosphorus	2.5	2.1	4.2	3.2	4.7	3.4
Sulfur	0.9	0.8	2.3	2.3	2.2	2.5
Magnesium	2.0	1.7	2.4	2.0	2.8	3.1
Potassium	10.0	8.7	35.4	25.7	30.3	23.3
Sodium	0.01	0.02	0.3	0.2	0.3	0.4
Chloride	2.0	2.2	8.1	7.2	4.4	12.1
Composition (mg/kg DM)						
Iron	96	112	179	152	134	285
Zinc	24	22	33	27	33	30
Copper	5	4	16	7	10	10
Manganese	19	19	33	36	35	54
Molybdenum	0.3	0.5	1.2	0.9	2.9	1.4
Fermentation analysis (g/100 g DM)						
Acetic acid	1.63	1.49	3.11	2.44	1.13	0.87
Propionic acid	0.14	0.14	0.16	0.22	0.05	0.15
Butyric acid	0.02	0.03	0.25	0.05	0.00	0.04
Lactic acid	1.33	1.97	0.94	2.34	0.85	1.29
Total acids	3.12	3.63	4.48	5.06	2.03	2.37
Ammonia	0.11	0.13	0.36	0.28	0.19	0.24
pH	4.11	3.82	4.70	4.15	4.90	4.53

digestibility was calculated by the ratio technique using the concentrations of the nutrients and chromic oxide in the diet and feces (Maynard et al., 1979).

2.2.3. Statistical analyses

Data were analyzed as a crossover design using the GLM procedures of SAS. The model used was: $Y_{ijkl} = \mu + S_i + C_j(S_i) + P_k + T_l + e_{ijkl}$ where μ is the overall mean, S_i is the effect

Table 7

In vitro nutrient digestibility of diets supplemented with 0, 50, or 100 g malic acid per cow per day that were fermented in a continuous culture system (experiment 1)

Item	Supplemental malic acid (g per cow per day)			S.E.M. ^c	P
	0	50	100		
Digestion coefficient					
Dry matter	0.718	0.719	0.796	0.032	0.22
Organic matter	0.459	0.480	0.514	0.018	0.16
Crude protein	0.515	0.599	0.629	0.034	0.13
Acid detergent fiber	0.521 ^b	0.547 ^{a,b}	0.589 ^a	0.015	0.04
Neutral detergent fiber	0.485 ^b	0.516 ^{a,b}	0.536 ^a	0.009	0.02
Nonstructural carbohydrate	0.782	0.732	0.757	0.018	0.23
Total carbohydrate ^d (g/day)	42.3	41.0	42.6	0.7	0.26

^a Least square means within a row without a common superscript differ ($P < 0.05$).

^b Least square means within a row without a common superscript differ ($P < 0.05$).

^c Standard error of least squares means.

^d g NDF + g NSC digested per day.

of sequence ($i = 1$ or 2), $C_j(S_i)$ is the effect of cow within sequence ($j = 1-20$), P_k is the effect of period ($k = 1-2$), T_l is the effect of treatment ($l = 1-2$), and e_{ijkl} is the residual. Least squares means were reported. Significance was declared at $P < 0.05$.

Dry matter intake was characterized but no statistical analysis was conducted because the cows were group-fed.

3. Results and discussion

3.1. Experiment 1: continuous culture

Digestibility of DM and OM was not affected ($P > 0.05$) by malic acid supplementation (Table 7). However, DM digestibility was higher than OM digestibility (Table 7) due to buffer salt contamination of the effluent. Digestibility of CP and NSC was not affected ($P > 0.05$) by malic acid supplementation (Table 7). Interestingly, CP digestibility numerically increased with increased malic acid supplementation. Digestibility of ADF and aNDF was higher ($P < 0.05$) when malic acid was supplemented at 100 g per cow per day compared to 0 g per cow per day; 50 g per cow per day supplemental malic acid was intermediate (Table 7). In a semi-continuous culture system given a diet with a 50:50 forage to concentrate ratio, the addition of malic acid (~ 5 mM) to the diet increased hemicellulose digestibility and tended to increase DM, OM, and NDF digestibility, but had no effect on ADF and cellulose digestibility (Carro et al., 1999). In another semi-continuous culture system (Gómez et al., 2004), DM and NDF digestibility was higher when diets (60:40 and 10:90 forage to concentrate ratio) were supplemented with 6.65 mM malic acid.

Malic acid supplementation did not affect ($P > 0.05$) the production of total VFA, propionic acid, butyric acid, and isobutyric acid, or the ratio of acetic to propionic acid (Table 8). However, 50 g per cow per day had the lowest ($P < 0.05$) acetic and lactic acid production and

Table 8

Volatile fatty acid (VFA) production, lactic acid production, and average daily fermenter pH of diets supplemented with 0, 50, or 100 g malic acid per cow per day that were fermented in a continuous culture system (experiment 1)

Item	Supplemental malic acid (g per cow per day)			S.E.M. ^c	P
	0	50	100		
VFA (mmol per day)					
Total	462.2	434.6	441.4	14.5	0.41
Acetic	276.1 ^a	235.2 ^b	266.6 ^a	5.4	0.004
Propionic	108.3	110.6	99.7	19.7	0.92
Butyric	59.5	65.2	56.1	5.8	0.56
Isobutyric	3.1	3.0	3.2	0.3	0.91
Valeric	11.9 ^b	16.7 ^a	12.0 ^b	1.2	0.04
Isovaleric	3.2	2.9	3.8	0.8	0.67
Acetic:propionic ratio	2.7	2.3	2.9	0.5	0.64
Lactic acid (mmol per day)	2.63 ^a	2.19 ^b	2.81 ^a	0.12	0.03
pH	6.10	6.11	6.08	0.07	0.95

^a Least squares means within a row without a common superscript differ ($P < 0.05$).

^b Least squares means within a row without a common superscript differ ($P < 0.05$).

^c Standard error of least squares means.

the highest ($P < 0.05$) valeric acid production (Table 8). It is unclear why there was a response at 50 g but not at 100 g of malic acid (Table 8). Possibly, the 100 g of malic acid was greater than the optimal dose under the dietary conditions of the study. There could have been a deficiency of a microbial growth factor with the 100 g of malic acid. The decrease in lactic acid production was expected. Nisbet and Martin (1991) reported that lactic acid uptake and utilization by *Selenomonas ruminantium* was stimulated in the presence of malic acid.

There were no significant differences ($P > 0.05$) among treatments in the average fermenter pH (Table 8). Castillo et al. (2004) suggested that malic acid supplementation could prevent a decrease in ruminal pH and acidosis by stimulating lactic acid uptake by *Selenomonas ruminantium*. The continuous culture system used in this study was buffered with artificial saliva and may not have been appropriate to study the effect of malic acid on ruminal pH. In addition, diet composition may explain the lack of effect of malic acid supplementation on total VFA production and pH. Positive responses to malic acid supplementation on ruminal fermentation and pH have been with relatively high-grain diets. On a lactating cow diet with a 50:50 forage to concentrate ratio (Kung et al., 1982), ruminal VFA concentrations and pH were not affected by malic acid supplementation. However, ruminal fluid samples were collected by stomach tube which may have affected the pH results.

Ammonia N concentration, non-ammonia N production, and non-ammonia, non-microbial N production were not affected ($P > 0.05$) by malic acid supplementation (Table 9). Microbial N production increased ($P < 0.05$) as malic acid supplementation increased (Table 9). Efficiency (g microbial N per kg of nutrient digested) of use of OM and total carbohydrate (aNDF plus NSC) was higher ($P < 0.05$) for the malic acid supplemented treatments compared to the control treatment. Microbial efficiency is maximized when the microbial nutrient balance for optimal growth is met, thus resulting in high microbial yield. The increased microbial efficiency observed in this experiment may be related to decreased lactic acid production or increased lactic acid utilization by bacteria, such as *Selenomonas*

Table 9

Nitrogen partitioning, microbial efficiency, and microbial composition of diets supplemented with 0, 50, or 100 g malic acid per cow per day that were fermented in a continuous culture system (experiment 1)

Item	Supplemental malic acid (g per cow per day)			S.E.M. ^d	P
	0	50	100		
Nitrogen (N) partitioning					
Ammonia N (mg/dl)	5.05	3.90	3.19	0.99	0.46
Non-ammonia N (g/day)	3.06	3.09	3.13	0.03	0.42
Microbial N (g/day)	1.49 ^c	1.89 ^b	2.10 ^a	0.05	0.002
Non-ammonia, non-microbial N (g/day)	1.57	1.21	1.04	0.11	0.13
Efficiency					
g Microbial N per kg DM ^e digested	20.8	26.8	26.6	2.0	0.12
g Microbial N per kg OM ^f digested	34.7 ^b	43.3 ^a	44.3 ^a	2.2	0.04
g Microbial N per kg TC ^g digested	35.1 ^b	46.6 ^a	50.3 ^a	1.0	0.001
g Microbial N per 100 g feed N digested	89.0	93.8	95.0	2.6	0.25
Composition of microbes					
N (g/kg DM)	74.6	86.1	75.2	8.1	0.56
Ash (g/kg DM)	256.8	208.1	256.6	44.7	0.69
RNA-N (g/kg microbial N)	114.0	112.3	109.8	6.2	0.89

^a Least squares means within a row without a common superscript differ ($P < 0.05$).

^b Least squares means within a row without a common superscript differ ($P < 0.05$).

^c Least squares means within a row without a common superscript differ ($P < 0.05$).

^d Standard error of least squares means.

^e DM: dry matter.

^f OM: organic matter.

^g TC: total carbohydrate = NDF plus NSC.

ruminantium. There was no effect of supplementation ($P > 0.05$) on efficiency of use of DM or feed N for microbial N. These findings provide evidence that the improvements in efficiency of microbial N production did not result from altered efficiency of protein fermentation overall. The results were probably mediated through changes in digestibility of carbohydrates (fiber) and consequently, digestibility of OM.

No differences ($P > 0.05$) in content of N, ash or RNA-N were detected (Table 9), indicating that no major shifts in microbial species resulted due to malic acid supplementation. In contrast, Gómez et al. (2004) found that malate increased the growth of solid-associated bacteria, but not liquid-associated bacteria in Rusitec fermenters fed a 60:40 forage to concentrate ratio diet.

3.2. Experiment 2: production study

Dietary malic acid varied between periods 1 and 2 (Table 4). During period 1, cows fed the control and supplemental malic acid diets consumed 145 and 186 g malic acid per cow per day, respectively assuming a DM intake of 24.6 kg DM per day. During period 2, cows fed the control and supplemental malic acid diets consumed 177 and 200 g malic acid per cow per day, respectively assuming a DM intake of 24.6 kg DM per day. The amount of supplemental malic acid was kept constant at 50 g per cow per day between periods 1 and

Table 10

Milk yield, milk composition, body weight (BW) change and body condition score (BCS) change of cows fed a diet containing no supplemental malic acid (control) or a diet supplemented to provide 50 g malic acid per cow per day (malic acid) (experiment 2)

	Diet		S.E.M ^a	P			
	Control	Malic acid		Diet	Period	Seq ^b	Cow (Seq)
Milk yield							
7-day mean milk ^c (kg/day)	36.8	38.3	0.4	0.01	0.05	0.01	<0.001
Sample-day milk ^d (kg/day)	37.6	39.3	0.5	0.02	0.03	0.05	<0.001
35 g/kg FCM ^e (kg/day)	39.2	40.5	0.5	0.10	<0.001	<0.001	<0.001
ECM ^f (kg/day)	39.0	40.3	0.5	0.07	<0.001	<0.001	<0.001
Milk composition							
Fat (g/kg)	37.9	37.0	0.4	0.12	<0.001	<0.001	<0.001
Fat (kg/day)	1.42	1.45	0.02	0.29	<0.001	<0.001	<0.001
True protein (g/kg)	30.8	30.8	0.1	0.83	<0.001	<0.001	<0.001
True protein (kg/day)	1.15	1.21	0.02	0.04	0.38	0.006	<0.001
Lactose (g/kg)	48.0	48.2	0.1	0.43	0.45	0.92	<0.001
Lactose (kg/day)	1.82	1.90	0.03	0.02	0.08	0.10	<0.001
Urea N (mg/dl)	7.94	8.01	0.16	0.77	<0.001	0.98	<0.001
Linear SCC ^g	3.86	3.80	0.07	0.60	0.18	0.001	<0.001
BW change ^h (kg)	18.6	21.5	2.9	0.49	0.22	0.22	0.85
BCS change ^h	0.05	0.04	0.03	0.73	0.49	0.49	0.84

^a Standard error of least squares means.

^b Sequence.

^c Mean of daily milk yield during the last 7 day of each period.

^d Sample day milk yield from which milk component yield was calculated.

^e Fat-corrected milk; 35 g/kg FCM = [(0.4324 × kg milk) + (16.216 × kg milk fat)].

^f Energy-corrected milk; ECM = [(0.327 × kg milk) + (12.95 × kg milk fat) + (7.20 × kg milk protein)] (Tyrrell and Reid, 1965).

^g Somatic cell count; linear SCC = ln (SCC/1000).

^h Change over a 28-day period (end of period BW/BCS minus beginning of period BW/BCS).

2. The difference in malic acid composition of the diets from periods 1 to 2 was probably a result of a change in the basal content of malic acid in individual feedstuffs. Unfortunately, individual feedstuffs were not analyzed for malic acid. A change from 3rd cut to 4th cut alfalfa-grass silage was made from periods 1 to 2. The 4th cut alfalfa-grass silage may have had more malic acid than the 3rd cut alfalfa-grass silage.

Cows fed the diet supplemented with malic acid had higher milk yield (P=0.01), milk true protein yield (P=0.04), and milk lactose yield (P=0.02) compared with cows fed the control diet (Table 10). Fat-corrected milk (35 g/kg) and energy-corrected milk tended to be higher in cows fed the malic acid diet compared with cows fed the control diet (Table 10). Previous studies have shown mixed results of malic acid on milk yield. In a few studies (Alferez, 1978; Stallcup, 1979; Devant and Bach, 2004), milk yield increased with malic acid supplementation. In contrast, two other studies (Kung et al., 1982; Vicini et al., 2003) observed no effect of malic acid on milk yield. The reason for the difference among studies is unclear but may be due to differences in the basal content of malic acid in the diets or the dose of malic acid supplemented. In this experiment, milk fat content and yield, true protein content, lactose content, milk urea N concentration, and somatic cell counts were not

Table 11

Total tract nutrient digestibility from cows fed a diet containing no supplemental malic acid (control) or a diet supplemented to provide 50 g malic acid per cow per day (malic acid) (experiment 2)

	Diet		S.E.M. ^a	P			
	Control	Malic acid		Diet	Period	Seq ^b	Cow (Seq)
Digestion coefficient							
Dry matter	0.679	0.673	0.005	0.43	0.76	0.009	0.89
Organic matter	0.681	0.677	0.004	0.44	0.17	0.005	0.31
Crude protein	0.623	0.629	0.006	0.47	0.06	0.10	0.04
Acid detergent fiber	0.474	0.479	0.009	0.70	0.99	0.003	0.34
Neutral detergent fiber	0.467	0.462	0.011	0.76	0.99	0.24	0.42
Hemicellulose	0.452	0.428	0.025	0.53	0.96	0.21	0.84
Cellulose	0.546	0.559	0.010	0.35	0.63	0.01	0.60
Ether extract	0.806	0.806	0.010	0.99	0.001	0.08	0.74
Starch	0.960	0.960	0.003	0.95	0.62	0.14	0.22
Nonfiber carbohydrate	0.897	0.900	0.007	0.75	0.70	0.20	0.19

^a Standard error of least squares means.

^b Sequence.

affected ($P>0.05$) by malic acid supplementation (Table 10). Similarly, Kung et al. (1982) and Devant and Bach (2004) observed no change in milk composition (Kung et al., 1982), but Alferez (1978) and Stallcup (1979) observed an increase in fat percentage with malic acid supplementation.

Period effects (Table 10) were significant for milk yield ($P=0.05$), content and yield of milk fat ($P<0.001$), content of milk true protein ($P<0.001$), and milk urea N concentration ($P<0.001$). The difference in malic acid intake between cows fed control and supplemental malic acid diets was greater in period 1 than 2 (41 g per cow per day versus 23 g per cow per day) and may explain the period effects. Sequence of treatment assignment to the cows during the two periods was significant ($P<0.01$) for content and yield of milk fat and true protein, and somatic cell counts. Cow within sequence was significant ($P<0.001$) for milk yield and milk composition.

Cows gained BW and body condition during the experiment (Table 10). However, there was no effect ($P>0.05$) of malic acid supplementation on BW change or BCS change (Table 10). Estimated DM intake was similar between cows group-fed the control diet (24.6 ± 1.4 kg per cow per day) and cows group-fed the malic acid diet (24.7 ± 0.4 kg per cow per day). In contrast, Stallcup (1979) found that cows fed a high-forage diet supplemented with 70 g malic acid compared to 0 or 28 g malic acid had higher BW gain and DM intake.

Total tract digestibility of DM, OM, CP, ADF, aNDF, hemicellulose, cellulose, ether extract, starch, and NFC was not affected ($P>0.05$) by malic acid supplementation (Table 11). Similarly, in steers fed moderate-forage diets (490 g concentrate/kg DM) supplemented with 0, 42, or 84 g malic acid per day (Kung et al., 1982) or in steers fed high-concentrate finishing diets supplemented with 0 or 80 g malic acid per day (Montaño et al., 1999), malic acid supplementation did not affect total tract digestion of DM (Kung et al., 1982), OM (Montaño et al., 1999), ADF (Kung et al., 1982; Montaño et al., 1999), starch (Montaño et al., 1999), or CP (Kung et al., 1982; Montaño et al., 1999).

Computer models have been developed for various purposes, including instruction of the basic principles of nutrition, formulation and evaluation of rations, hypothesis testing, and research planning. The CPM Dairy[®] nutrition model provided a quick and inexpensive way to evaluate the microbial efficiency data of experiment 1 and model the production results of experiment 2. The increase in milk yield with no increase in nutrient digestibility of the diet may be explained by an increase in microbial efficiency, as observed in experiment 1. To test the hypothesis of increased microbial efficiency, the bacterial maximum yield parameters in the CPM Dairy[®] nutrition model were changed from 0.40 to 0.42 to reflect the observed changes in microbial efficiency for experiment 1. This change in microbial efficiency allowed metabolizable protein allowable milk (limiting compared to metabolizable energy allowable milk) to increase ~1.5 kg, which was similar to the treatment difference observed in experiment 2. The modeling exercise emphasized the importance of exploring factors that affect microbial efficiency and the need to adjust model equations and parameters based on research results versus hypothetical situations.

4. Conclusions

Supplementing corn-based diets for dairy cows with malic acid had a significant effect on some fermentative processes in the rumen as assessed by a continuous culture system. Microbial N and microbial efficiency increased with supplemental malic acid (equivalent to 50 g per cow per day). Cows that were fed 50 g supplemental malic acid per day increased milk yield with minimal effect on milk composition. Based on several in vitro studies, it is possible that supplementing dairy cow diets with malic acid might be effective in reducing subclinical ruminal acidosis by stimulating lactate utilization by *Selenomonas ruminantium* and decreasing the drop in ruminal pH after feeding. This concept needs to be evaluated in vivo. Inclusion of malic acid as a feed additive in diets for dairy cows is expensive (\$0.11 per cow per day) and may not be economically feasible at this time. However, forages high in organic acids might provide a vehicle for inclusion of malic acid in diets for dairy cows.

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