ABSTRACT: Use of coproducts such as corn and sorghum distillers grain (DG) and corn gluten feed (CGF) in beef cattle finishing diets has increased significantly in recent years, but research to evaluate the efficacy of traditional feeding practices and feed additives when coproducts are fed has not kept pace. Grain processing methods that increase starch availability seem equally effective in traditional diets and diets with wet CGF; however, in wet DG diets, some studies have shown decreased efficacy of grain processing, whereas others have shown no evidence of an interaction. Limited data are available on the physical and nutritional value of the fiber in wet DG and CGF; however, CGF at concentrations ≥25% of the dietary DM seems to have some degree of “roughage value,” whereas fiber in wet DG seems to have less potential to replace traditional roughage sources. There is little evidence that efficacy of ionophores and antibiotics is changed with diets based on wet CGF or that they interact when wet DG is added to finishing diets. In vitro data from our laboratory suggest no loss of monensin efficacy in substrates with 15% (DM basis) corn DG in terms of changes in VFA and gas production. Moreover, efficacy of ionophores was not affected in our data by diet substrates with increasing concentrations of S, and in vitro H₂S production in substrates containing wet DG seems predictable from substrate S concentrations. Nonetheless, limited in vivo data indicate decreased ruminal acetate-to-propionate ratios in diets with increased wet DG, which may minimize the potential for ionophores to alter propionate. Likewise, in vivo results indicate that feeding wet DG may decrease ruminal pH; thus, to maximize DMI and minimize digestive upsets, optimal concentrations of roughage need to be evaluated in diets containing wet DG. Research is needed on other potential technology interactions with coproducts of biofuel production such as glycerol and condensed distillers solubles. The effects of yeast products and live microbial cultures in diets with coproduct feeds have generally not been determined. Because of the elevated fiber concentrations in CGF and DG, effects of exogenous enzyme preparations on ruminal fermentation and fiber digestion of diets containing these coproducts should be evaluated.

Key words: corn gluten feed, distillers grain, high-concentrate diet, ionophore

INTRODUCTION

Over the past 2 decades, rapid growth of wet corn milling for production of corn-based sweeteners and of dry milling of grain for fuel ethanol production has resulted in a remarkable increase in the use of coproducts from these processes (corn gluten feed (CGF) and distillers grains (DG, with or without condensed distillers solubles), respectively) in cattle feeding operations. These coproducts contain substantially more protein and fiber, and in the case of distillers grains, more fat, than the original grain. Concentration of nutrients, as well as addition of nutrients or other exogenous components (e.g., S in both CGF and DG, yeast cells and antibiotics in DG), adds further changes from the original grain that might complicate the use of these coproducts in practice. Moreover, in commercial feedlots, CGF and DG are often fed as high-moisture products, which imposes limits on shelf life and increases the risk of spoilage and mold growth. In addition to grain-based coproducts such as CGF and DG, production of biodiesel from oilseeds and other fat or oil stocks results in glycerol, which has potential applications in both ruminant and nonruminant feeding operations (Lammers et al., 2008; Parsons et al., 2009).
With substantive compositional and physical differences, it is logical to question whether diets containing relatively greater concentrations of grain coproducts or glycerol respond in a similar manner to tried-and-true diet formulation approaches (e.g., roughage amount and source) and technologies (e.g., grain processing and feed additives) used with traditional grain-based feedlot diets. Our objective is to summarize the current literature with respect to the efficacy of standard feeding practices and feed additives in diets containing coproduct feeds, with particular emphasis on CGF and DG.

**GRAIN PROCESSING**

*Traditional Feed Ingredients*

Processing of cereal grains is widely used in the feedlot industry to increase starch availability and thereby enhance animal performance. Additional benefits of cereal grain processing include destruction of mycotoxins and improvements in mixing characteristics of the diet (Owens et al., 1997). The most popular feedlot cereal grain processing methods are steam flaking, dry rolling, high-moisture harvesting and storage, and to a lesser extent, tempering and grinding. Steam flaking is a particularly effective method, especially for corn and sorghum. In a summary of 8 trials comparing the effects of corn processing, an average increase of 18.8% in NE\textsubscript{g} concentration was reported for steam-flaked corn (SFC) vs. dry-processed corn (Zinn et al., 2002). Improved feed efficiency resulting from steam flaking is due to increased starch digestibility, as well as greater digestion of the nonstarch OM (Zinn et al., 2002). Zinn et al. (1995) reported a 9% increase in total tract starch digestion for SFC vs. dry-rolled corn (DRC); however, the digestibility of the nonstarch OM was increased by flaking to the same degree (10%). This finding indicates that the structural changes in cereal grains associated with steam flaking affect both starch and nonstarch components. Decreases in ruminal methane production are typically observed with diets based on steam-flaked grain, which result from a shift in VFA production that favors increased propionate (Johnson et al., 1968; Zinn et al., 2002). Nonetheless, the benefits of decreased methane with steam flaking might be offset by a shift in site of digestion (e.g., greater ruminal digestion) compared with dry-processed grain (Zinn et al., 2002).

*Newer Feed Ingredients*

The replacement of high-moisture corn (HMC) or DRC by distillers grains plus solubles (DGS) on a dry weight basis in feedlot diets has increased ADG and G:F, with the magnitude of the improvement being greater for wet DGS (WDGS) than dried DGS (DDGS; Klopfenstein et al., 2008). A meta-analysis involving 9 studies, in which either DRC or HMC was the primary grain in the diet, revealed a quadratic response in G:F as WDGS increased in the diet, with maximal G:F at a 30 to 50% dietary inclusion level (Klopfenstein et al., 2008). When a similar analysis was conducted with DDGS, a cubic response of G:F was observed as DDGS increased from 0 to 40% of the dietary DM, with G:F maximized at 10 to 20% inclusion (Klopfenstein et al., 2008). Differences in G:F observed between DDGS and WDGS may be related to the presence of volatile compounds (e.g., ethanol and organic acids) in WDGS that are lost during drying, similar to what has been documented for wet CGF (WCGF; Stock et al., 2000). Assuming the feeding value of ethanol is equal to grain and that ethanol is lost during DM determination, Cole et al. (2009) suggested that the presence of ethanol in WDGS could potentially increase its energy value by 10% or more. Alternatively, changes in the protein fraction of DDGS during the drying process might affect the availability of protein, and consequently performance (Owens, 2008).

The inclusion of WCGF in high-grain diets has increased DMI and ADG, regardless of processing method of the basal grain (Stock et al., 2000; Scott et al., 2003; Parsons et al., 2007). A summary of 5 finishing trials with inclusion levels of WCGF ranging from 20 to 60% (DM basis) indicated an improvement of 5.1% in feed efficiency over control diets without WCGF (Stock et al., 2000). Scott et al. (2003) reported that inclusion of 22% WCGF (DM basis) in DRC- or SFC-based diets did not affect G:F compared with control diets; however, when WCGF was included as 32% of the dietary DM, a decrease in G:F vs. control diets was observed in DRC-based diets, but not in SFC-based diets. Loe et al. (2006) reported no effects on G:F when feeding feedlot steers barley-based diets with WCGF inclusion levels ranging from 0 to 69% of the DM. Parsons et al. (2007) reported decreased G:F in steers fed SFC-based diets containing 20 or 40% WCGF (DM basis) compared with control diets that did not contain WCGF. Thus, despite a consistent response in DMI and ADG, there seems to be a somewhat inconsistent G:F response with the addition of WCGF to finishing diets. Given the potential beneficial effects of WCGF inclusion on acidosis (Krehbiel et al., 1995), Scott et al. (2003) suggested that variation in the potential for development of subacute acidosis with extensive grain processing might be one reason for the inconsistent G:F response. Variation in nutrient composition among coproduct sources used in different studies could affect the G:F response. In addition, a dilution effect in the energy density of the diet as WCGF replaces basal grain(s) could be responsible for decreased G:F in finishing diets with relatively high concentrations of WCGF.

An interaction (\( P < 0.01 \)) between corn processing method and the inclusion level of corn WDGS was reported by Corrigan et al. (2007). A linear increase (\( P < 0.01 \)) in G:F was observed for DRC and HMC as corn WDGS increased from 0 to 40% of the dietary DM, but...
no effects \((P > 0.10)\) were noted on G:F when WDGS replaced corn in SFC-based diets. Similarly, a corn processing method × sorghum WDGS level interaction \((P < 0.01)\) was reported by May et al. (2007), indicating a decreased response in G:F when up to 30% sorghum WDGS was included in SFC-based diets compared with a positive response in G:F for DRC-based diets. Drouillard et al. (2005) reported a quadratic response in G:F when feeding SFC-based diets to finishing heifers with inclusion levels of sorghum WDGS ranging from 8 to 40% of the dietary DM. Drouillard et al. (2005) concluded, based on G:F data, that the optimal inclusion level of sorghum WDGS was between 8 and 16% of the DM, with a similar G:F response in heifers fed 0 or 24% sorghum WDGS in the DM. In contrast, Leibovich et al. (2009) reported that the inclusion of 15% sorghum WDGS in the DM of feedlot diets decreased G:F in finishing steers compared with a control diet, regardless of grain processing method (SFC or DRC). Although few direct comparisons have been made, differences observed in performance between corn and sorghum WDGS when included in finishing diets emphasize the need to accurately describe the nature of the coproduct (i.e., the grain base, inclusion rate of solubles, and so on) used in experimental diets.

A series of studies by Corrigan et al. (2008a,b) attempted to explain the cause of the interaction observed between grain processing method and concentration of corn WDGS in the diet. Despite the lack of an interaction \((P > 0.10)\) between corn processing method and concentration of corn WDGS in the diet (0 or 40%), ruminal pH change, maximal pH, and acetate-to-propionate ratio \((A:P)\) tended \((P < 0.09)\) to be greater for steers fed 0% WDGS than for steers fed 40% WDGS (Corrigan et al., 2008b). Even with the greater NDF intake \((P < 0.05)\) reported by Corrigan et al. (2008b) for steers fed WDGS vs. the control, the tendency for a reduced A:P in steers fed WDGS may imply that the fermentation of the fiber fraction in WDGS is somewhat impaired, perhaps because of reduced ruminal pH. It is widely recognized that the fermentation of fiber favors an increase in A:P (Murphy et al., 1982; Lana et al., 1998) and that ruminal cellulolytic activity is decreased at a ruminal pH below 6.0 (Kovacik et al., 1986). Given the range of ruminal pH and the time spent at a ruminal pH below 5.6 reported by Corrigan et al. (2008a) with 40% corn WDGS in the diet, it could be possible that ruminal NDF fermentation was hindered, at least temporarily. If ruminal fermentation of NDF is affected by a decreased pH related to feeding greater concentrations of DGS, it is logical to expect a further decrease in pH (and thus in cellulolysis) with SFC vs. DRC or HMC. In support of this hypothesis, Vander Pol et al. (2009) reported a decreased \((P < 0.10)\) A:P in steers fed 40% corn WDGS vs. a control DRC-based diet; these differences were observed despite a greater \((P < 0.10)\) NDF intake by steers fed WDGS. No statistically significant differences were observed in ruminal pH in the study by Vander Pol et al. (2009), although average pH was less for steers fed WDGS vs. the control (5.24 vs. 5.37). In agreement with the results of Corrigan et al. (2008b) and Vander Pol et al. (2009), Uwituze et al. (2008) reported a reduced \((P < 0.05)\) A:P when 25% DDGS was included in steer finishing diets based on SFC. Whether a decreased ruminal pH or a shift in the A:P is partially responsible for the interaction between grain processing method and DGS feeding is not clear, but the present data indicate these issues merit further investigation.

The observation of decreased ruminal A:P in WDGS diets despite a greater NDF intake is puzzling, and careful evaluation of ruminal fermentation patterns with diets containing increasing concentrations of WDGS is needed. One possible explanation for the decrease in A:P when DGS is fed might be the composition of NDF in DGS. Characterization of the fiber fraction in 46 samples of DDGS revealed an average concentration of hemicellulose (calculated by subtracting ADF from the NDF values reported) of 15.4% (Stein and Shurson, 2009), which is approximately twice the hemicellulose content of corn (NRC, 2000). Thus, replacing corn with DGS would increase the percentage of hemicellulose in the diet. The fermentation of hemicellulose by ruminal microorganisms has been reported to yield a more reduced A:P than observed with the fermentation of cellulose (Murphy et al., 1982). If NDF intake increases \((P < 0.10)\) by 50% in diets containing 40% WDGS compared with DRC (Vander Pol et al., 2009), given the changes in concentration of hemicellulose in corn grain vs. DGS, the intake of hemicellulose would more than double with the WDGS diet. Thus, this change in the quantity of hemicellulose being fermented in the rumen might be partially responsible for the decreased A:P when feeding WDGS. Fermentation of the solubles fraction of WDGS also might provide another possible explanation for a decreased A:P when feeding WDGS. Ham et al. (1994) observed a decrease \((P < 0.1)\) in A:P when 20% thin stillage (DM basis) was supplemented to a diet containing 57% DRC. Other factors, such as total and unsaturated fat intake (Zinn, 1989) and changes in the kinetics of digestion (i.e., passage and digestion rates), also should be considered because they may affect ruminal fermentation and the resulting A:P.

The decrease in A:P along with increased digestion of fat and an increased flow of unsaturated fatty acids reaching the duodenum have been proposed as possible mechanisms associated with the improvements in G:F observed with the addition of corn WDGS to DRC- and HMC-based diets (Vander Pol et al., 2009). Because of an increased content of NDF relative to corn, the inclusion of more than 20% DGS in finishing diets was initially thought to decrease the likelihood of subacute acidosis or even allow the roughage content of the diet to be decreased (Klopfenstein et al., 2008). These effects on acidosis and “roughage value” have been documented with WCGF feeding (Krehbiel et al., 1995;
Because ruminal pH has been shown to decrease when thin stillage was added to DRC-based diets (Ham et al., 1994), it is possible that the effect of feeding DGS on ruminal pH depends on the proportion of thin stillage in the final product. It also is possible that any beneficial effects of WCGF feeding in terms of subacute acidosis prevention are related to the composition of the condensed fermented corn extractives (heavy steepwater) added back to WCGF, which differs from the thin stillage (solubles) fraction generated in the dry-milling process. The concentration of lactic acid in the heavy steepwater resulting from wet milling can be as much as 25% (R. A. Stock, Cargill Inc., Blair, NE, personal communication), and the proportion of this liquid fraction added back to WCGF can vary greatly from plant to plant (Stock et al., 2000). Increased quantities of lactic acid entering the rumen could predispose the ruminal environment to the presence of lactic acid and promote the growth of lactolytic bacteria, which, in turn, could metabolize lactate resulting from the ruminal fermentation and prevent its accumulation, thereby decreasing the likelihood of ruminal acidosis. The metabolism of ruminal lactate as a means of preventing subacute acidosis has been suggested as a mode of action associated with supplementing lactate-producing bacteria to ruminants (Krehbiel et al., 2003) or when stimulating lactate uptake by the addition of organic acids, such as L-malate, to in vitro cultures of lactate-utilizing bacteria (Nisbet and Martin, 1994). In support of this hypothesis, Fron et al. (1996) conducted in vitro experiments with ruminal fluid from cattle adapted to a diet containing distillers solubles and found increased counts of lactate-utilizing bacteria, as well as an increased rate of lactate fermentation compared with fluid from cattle that were not adapted to distillers solubles.

Perhaps the primary differences between the effects of WCGF and WDGS on ruminal pH are a result of the physical nature of the fiber fraction in these 2 coproducts. Lodge et al. (1997) indicated that the larger particle size in WCGF compared with DGS might result in a decrease in passage rate, thereby increasing ruminal NDF digestibility of WCGF. Firkins et al. (1985) stated that the combination of larger particle size and flakier texture in WCGF could lead to greater ruminal NDF digestibility. Differences in particle size and texture between WDGS and WCGF might also account for a greater roughage value, and thus a greater effect on acidosis prevention for WCGF than for WDGS. In addition to changes in ruminal fermentation patterns, Parsons et al. (2007) reported altered eating patterns by steers fed 40% WCGF relative to those on a control diet composed of 74% SFC, indicating that changes in eating behavior also may be related to the potential for decreasing subacute acidosis with WCGF.

### MODIFICATION OF ROUGHAGE SOURCE AND AMOUNT

#### Traditional Feed Ingredients

To optimize production efficiency and minimize the logistics of handling bulky materials, inclusion of forage is typically minimized in feedlot diets. Thus, the energetic contribution of fiber is very small relative to that of the cereal grains, and addition of roughage is often associated with the purpose of maintaining a healthy rumen and minimizing digestive upsets. In a meta-analysis of literature data, Arelovich et al. (2008) reported positive linear relationships between dietary NDF and DMI ($r^2 = 0.96$), as well as a strong positive association between dietary NDF concentration and NE$_g$ intake ($r^2 = 0.86$) in beef cattle diets ranging from 7.5 to 35.3% NDF. Because DMI and particularly NE$_g$ intake are key factors in determining cattle performance, manipulating dietary NDF concentration by altering the amount of dietary roughage can be an effective tool to enhance animal productivity. The physical or chemical characteristics of the fiber in different roughage sources can affect ruminal fermentation, as well as the site and extent of digestion (Galván and Defoor, 2003). The substitution of more readily fermentable roughage sources, such as corn silage, with more physically effective sources, such as hay or straw, can increase rumination and alter eating patterns, thereby preventing the onset of metabolic disorders such as acidosis (Marshall et al., 1992; Krause et al., 1998).

Arelovich et al. (2008) suggested that roughage sources could be exchanged on the basis of their NDF concentration to achieve equal DM and NE$_g$ intakes. In agreement with the findings of Arelovich et al. (2008), Marshall et al. (1992) observed that when diets were formulated based on a similar NDF concentration, intake and total tract digestion of nutrients were not affected, except when feedstuffs acceptability was a factor. Theurer et al. (1999) found that, on an equal NDF basis, the inclusion of alfalfa hay (12% of dietary DM) increased G:F compared with diets containing a mixture of alfalfa hay and wheat straw, or alfalfa hay and cottonseed hulls. Differences in feed efficiency observed with diverse roughage sources fed to provide an equal percentage of dietary NDF may be associated with differences in digestibility of the fiber fraction, provided that CP and energetic density remain relatively similar across diets. Thus, even though roughage sources may be interchangeable on a dietary NDF basis to equalize DM and NE$_g$ intakes, factors intrinsic to the NDF fraction of the forage (e.g., content of hemicellulose and lignin) may affect nutrient utilization and metabolism, ultimately affecting ADG and G:F.

#### Newer Feed Ingredients

As noted previously, inclusion of DGS and CGF in feedlot diets decreases the concentration of starch and
increases the concentration of fiber relative to more traditional high-grain finishing diets. Nonetheless, the nature of the fiber added by newer feed ingredients varies among coproducts, and, as we have already discussed, little is known about the ruminal fermentation of various coproduct fiber sources. Given that increasing NDF concentrations in feedlot diets are associated with increased DMI (Arelovich et al., 2008), a DMI response might be expected with increased dietary concentrations of DGS or CGF; this assumes that corn is replaced by coproducts without changing the dietary roughage concentration. Nonetheless, the DMI response with coproducts varies depending on the coproduct. Increased DMI with the inclusion of WCFG in finishing diets has been reported in several experiments (Stock et al., 2000; Scott et al., 2003; Parsons et al., 2007). In contrast, inclusion of 15% sorghum WDGS (DM basis) in finishing diets did not affect DMI, regardless of corn processing method in the basal diet (Leibovich et al., 2009). Drouillard et al. (2005) reported a linear decrease in DMI with increasing sorghum WDGS concentrations ranging from 0 to 40% of the dietary DM, whereas Vander Pol et al. (2009) observed no effects on DMI with the inclusion of up to 40% corn WDGS (DM basis) in DRC-based diets. Similarly, Depenbusch et al. (2008) reported no effects on DMI when adding corn WDGS (0 or 25% of dietary DM) to SFC-based diets.

With WCFG, a tendency (P = 0.09) for an interaction between the dietary content of alfalfa hay (0, 3.75, or 7.5% of dietary DM) and WCFG content (0 or 35% of dietary DM) was observed for G:F of steers fed a DRC-based diet (Farran et al., 2006). The G:F increased as alfalfa hay increased in diets without WCFG, whereas increased alfalfa hay decreased G:F in diets containing 35% WCFG (DM basis). A detrimental effect on G:F of added roughage to diets containing WCFG was not as evident in the study by Parsons et al. (2007); however, decreased DMI was noted when roughage was completely removed in an SFC-based diet containing 40% WCFG (DM basis). Differences in grain processing method (DRC vs. SFC) might have contributed to different results in the studies by Farran et al. (2006) and Parsons et al. (2007). Sindt et al. (2003) conducted a series of studies to investigate possible interactions in ruminal metabolism and animal performance between WCFG (25, 35, or 45% of dietary DM) and alfalfa hay content (2 or 6% of dietary DM) in SFC-based diets. Despite the lack of interaction in any of the performance variables, the authors reported interactions (P < 0.05) between content of WCFG and alfalfa hay in ruminal fluid turnover time and volume, A:P, and WCFG ruminal degradation rate. Based on animal performance data, Sindt et al. (2003) concluded that alfalfa hay content could be decreased when WCFG is added at 25% or more of the dietary DM to SFC-based diets. Compared with WDGS, it seems that WCFG has some degree of efficacy in providing roughage value in finishing diets, but more research is needed to evaluate potential interactions between WCFG and dietary roughage concentration with different grain processing methods.

**FEED ADDITIVES**

**Traditional Feed Ingredients**

Ionophores, antibiotics, and probiotics are the most widely used feed additives in the beef cattle industry. Since the approval in the mid-1970s of monensin as a feed additive for ruminant diets, the use of ionophores in feedlot diets has expanded rapidly, and at present, ionophores (particularly monensin) are included in most conventional feeding programs in US feedlots. Previously, response summaries indicate improvements in feed efficiency of 7.5% with monensin (Goodrich et al., 1984), 5.6% with laiodynamycin propionate (Bauer et al., 1995), 7.5% with lasalocid (Berger et al., 1981), and 8.1% with salinomycin (Zinn, 1986); however, a more recent summary with monensin indicated somewhat lesser responses in highly processed grain diets than indicated by the older literature (Laudert, 1992). With respect to their mode of action, ionophores alter transport of ions across ruminal bacteria membranes, resulting in a shift in ruminal microbial populations that leads to decreased acetate and increased propionate (Russell and Strobel, 1989). Other effects of ionophores include decreased ruminal methane production and reduced ruminal ammonia concentrations, the latter as a result of decreased deamination of AA (Russell and Strobel, 1989).

Interest in the inclusion of probiotics in feedlot diets has increased in recent years as a result of growing public concern over the use of growth promoters in the animal feed industry, and potential beneficial effects on fecal shedding of foodborne pathogens (Stephens et al., 2007; Vasconcelos et al., 2008). The mode of action of probiotics depends largely on the type and dose of the microorganism fed. In a literature summary, an improvement of 2.5% in G:F was reported in feedlot cattle supplemented with lactate-utilizing bacteria, lactate-producing bacteria, or both (Krehbiel et al., 2003).

**Newer Feed Ingredients**

The use of sulfuric acid both to control pH during the fermentation and as a cleaning agent for the equipment in the production of starch-derived ethanol leads to an increased concentration of S in the resulting coproducts. Sulfur is an essential mineral for ruminants, and it can be supplied by the diet or in drinking water in the form of AA, sulfates, sulfites, or elemental S. The NRC (2000) recommended a maximum tolerable dietary concentration of S of 0.40% of the DM for beef cattle; however, dietary S concentrations of 0.25% (DM basis) have decreased feedlot cattle performance and carcass merit (Zinn et al., 1997). Excessive S intakes have been associated with the onset of polioencephalomalacia (Gould, 1998) via reduction of S by ruminal bacteria,
forming toxic H$_2$S that can be absorbed. The concentration of S varies greatly among coproducts and production facilities. In general, coproducts derived from the wet milling of corn, such as CGF, have a smaller range of S concentrations than those from dry milling, such as DGS (Crawford, 2007; Klopfenstein et al., 2008). The content of S in DGS has been reported to vary between 0.40 to 1.30% of DM in both WDGS and DDGS (Crawford, 2007; Klopfenstein et al., 2008). This elevated content of S in DGS is perhaps, along with the fat content, the main limiting factor for the inclusion of greater concentrations in beef cattle diets.

A series of in vitro experiments conducted by Kung et al. (2000) showed that addition of monensin to batch culture fermentations resulted in increasing H$_2$S production; however, these studies were conducted using ruminal fluid from donor cattle that were not adapted to monensin. In addition, the concentration of S in the incubation substrate used by Kung et al. (2000) was 1.09% of the DM, which is much greater than would be expected in beef cattle finishing diets. Recently, batch culture fermentation studies were conducted by Quinn et al. (2009) to evaluate 3 ionophores (i.e., monensin, lasalocid, and laidlomycin propionate) and 2 antibiotics (chlortetracycline and tylosin). There was no effect of the feed additives on H$_2$S production when the incubation substrate DM contained 0.42% S. In agreement with the results of Quinn et al. (2009), Smith et al. (2009) reported no effects of increasing concentrations of monensin on in vitro H$_2$S production with a high-grain substrate ranging from 0.2 to 0.8% S (DM basis). Moreover, the lack of effect of ionophores and antibiotics did not depend on adaptation of ruminal fluid donor cattle to monensin before collection of fluid for batch culture incubations.

Despite the fact that the commonly used feed additives do not seem to cause an increase in H$_2$S, concern remains regarding the greater S concentration of some of the newer feed ingredients and its potential for toxicity. Because of an inverse relationship between ruminal H$_2$S and pH (Gould, 1998), the effects of dietary roughage content on S toxicity need to be addressed. In addition, the development of feed additives with the ability to modify the ruminal microbial environment and to decrease counts of sulfate-reducing bacteria or to sequester H$_2$S should be a research priority to prevent S toxicity with many of the newer feed ingredients.

Improved G:F with ionophores has been observed in feedlot cattle regardless of grain processing method, although, as noted previously, the magnitude of response seems to be less with current diets and feeding practices (Laudert, 1992) than reported in the past (Goodrich et al., 1984). This diminished response is likely attributable to changes in ruminal fermentation end products that have resulted from decreased use of roughage, greater emphasis on grain processing, and addition of fat to diets. All these technologies lead to decreased A:P and methane concentrations (calculated from VFA data), as are typically observed in SFC- and HMC-based diets vs. DRC-based diets (Zinn, 1987; Cooper et al., 2002; Corona et al., 2006), leaving a smaller margin for improvement by addition of ionophores. Although the effects of ionophores on animal performance have been widely documented in diets containing SFC, DRC, or HMC as the base grain, studies of their effects in diets containing some of the newer feed ingredients, such as DGS, are not abundant in the peer-reviewed literature. Meyer et al. (2009) reported increased G:F when monensin or monensin plus tylosin were added to the diet of steers fed 25% WDGS (DM basis), with either DRC or SFC as the basal grain. Depenbusch et al. (2008) tested the efficacy of monensin and monensin plus tylosin in heifers fed SFC-based diets containing 25% corn WDGS. In contrast to the results of Meyer et al. (2009), no effects of feed additives ($P \geq 0.20$) or any feed additive × diet interactions ($P \geq 0.77$) were observed for heifer performance. Although responses are confounded with the study, it is interesting to note that the diets used by Meyer et al. (2009) included white grease to balance dietary treatments for total fat content, whereas in the study by Depenbusch et al. (2008), a greater dietary fat content was associated with the 25% corn WDGS treatment compared with the control (5.4 vs. 3.3% ether extract, DM basis). Differences in dietary fat content between studies may be responsible for differences in ionophore efficacy between the studies of Meyer et al. (2009) and Depenbusch et al. (2008). Decreased efficacy of ionophores has been reported with supplemental fat (Clary et al., 1993), which is possibly related to the effects of fat on methane production and A:P (Zinn, 1988). More research is needed regarding the efficacy of ionophores in diets with inclusion of some of the newer coproducts of the ethanol industry, particularly because efficacy may be affected by dietary fat content.

Effects of the addition of probiotics or bacterial enzymes to feedlot diets, including newer coproducts, have not been reported in the literature. Given the changes in dietary composition typically observed with increasing concentrations of DGS (greater NDF and fat content), further research is needed to determine any possible interactions between coproduct inclusion and probiotics. In addition, with beneficial effects observed from adding exogenous fibrolytic enzymes to ruminant diets (Beauchemin et al., 2003; Colombatto et al., 2003) and the greater NDF concentration associated with diets containing DGS and CGF, it seems reasonable to investigate possible effects of enzyme addition on fiber digestion and animal performance.

**LIQUID COPRODUCTS**

The rapid expansion of the biodiesel industry has led to an increased production of crude glycerin, a liquid coproduct resulting from the transesterification of vegetable oils (Mach et al., 2009). Glycerin seems to be useful as a conditioning agent, potentially serving a role similar to molasses or distillers solubles in de-
increasing dustiness and improving diet acceptability. Nonetheless, very little research has reported the effects of adding crude glycerin to beef cattle finishing diets; thus, little is known about possible interactions with grain processing methods, roughage source and amount, or feed additives. Parsons et al. (2009) fed crude glycerin concentrations ranging from 0 to 16% of the dietary DM to finishing heifers on an SFC-based diet. A linear decrease in DMI and a quadratic effect on ADG and G:F (both optimized at 2% crude glycerin inclusion) were noted with increasing crude glycerin concentrations, and the authors concluded that ADG and G:F were improved when crude glycerin was added at concentrations of 8% or less on a DM basis (Parsons et al., 2009). In contrast, Mach et al. (2009) reported no effects of feeding crude glycerin concentrations of up to 12% of the dietary DM on animal performance or carcass characteristics of Holstein bulls. Reasons for this discrepancy are not clear but might be related to the fact that the diets fed by Mach et al. (2009) were isonitrogenous and isocaloric (assuming an ME of 3.47 Mcal/kg for crude glycerin), whereas Parsons et al. (2009) replaced SFC with glycerin, adding soybean meal to balance for CP across diets. In addition, the basal grain used in both studies differed [ground corn and barley with Mach et al. (2009) vs. SFC with Parsons et al. (2009)], which may indicate a possible interaction between source or processing method of grain and addition of crude glycerin to beef finishing diets. Nonetheless, these differences are confounded with the study, so further research is needed to evaluate the utility of glycerol in finishing diets.

One additional concern with feeding glycerin is its methanol concentration (Sellers, 2008). The US Food and Drug Administration has indicated that, until otherwise demonstrated, crude glycerin with methanol concentrations >150 mg/kg is not suitable for use in animal feeds (Sellers, 2008). Nonetheless, few studies have examined whether such concentrations pose health and safety issues for ruminants. Feeding up to 12% (DM basis) crude glycerin with a methanol concentration of 900 mg/kg to Holstein bulls did not result in any detrimental effects on animal health (Mach et al., 2009). Methanol seems to be almost quantitatively converted to methane in the rumen (Pol and Demeyer, 1988); thus, crude glycerin with greater concentrations of methanol should have a reduced ME concentration. Further research is needed to clarify the role of methanol in the nutritional value of crude glycerin in feedlot diets, as well as possible interactions of glycerin with other ingredients and feeding technologies.

Liquid fractions derived from the dry and wet milling of grains have been used in beef finishing diets both to decrease dustiness and as sources of energy and protein. When a condensed distillers solubles product was offered free choice in beef finishing diets, total DMI did not change, but DMI from condensed distillers solubles was increased, leading to an increased G:F compared with control steers (Rust et al., 1990). The addition of 15% (DM basis) condensed distillers solubles or 20% thin stillage (DM basis) to a DRC-based diet decreased ruminal pH compared with a control diet (Ham et al., 1994). The presence of high concentrations of lactate, fumarate, malate, and succinate in condensed distillers solubles was reported by Fron et al. (1996). Added fumarate and malate have modified ruminal fermentation and decreased methane production in vitro (Ungerfeld et al., 2007) and in vivo (Martin et al., 1999; Foley et al., 2009). Concentrations of organic acids, along with the fat content in these liquid coproducts, may contribute to the decreases in ruminal pH observed in DRC-based diets when distillers coproducts are fed. The level of inclusion of liquids such as distillers solubles and thin stillage in dry- and wet-milling coproducts is not specified in most of the experiments currently reported in the literature, but this information would seem to be important in describing these products and delineating their effects on performance and ruminal fermentation. Little or no information is available on the effects of liquid fractions from the dry or wet milling of grains with different grain processing methods or as affected by dietary roughage concentration.

**Summary and Conclusions**

Based on the information we have reviewed, interactions of coproduct feeds with existing technologies are summarized in Table 1. As the biofuel industry continues to expand, increasing quantities of coproducts will be available for livestock feeding. Because not all the coproducts reviewed seem to respond similarly in combination with tried-and-true diet formulation approaches, potential interactions of newer coproducts with existing technologies for enhancing animal performance can be a challenge for nutritionists. Our review has indicated that further research is needed to address the interaction between DGS feeding and grain processing method. Possible reasons for this interaction may be related to changes in ruminal metabolism and fermentation of the fiber fraction, inhibitory effects of ruminal pH on cellulolytic bacteria populations, and metabolism of dietary fat. Thus, there is a need to know more about the effects of DGS on ruminal metabolism, especially its effect on ruminal pH and the fermentation of the NDF fraction. Moreover, compositional differences between liquid fractions derived from the dry or wet milling of corn may affect ruminal bacteria populations and the relationship of resulting coproducts to subacute acidosis. The biofuel industry has changed rapidly in recent years, such that modifications are constantly being introduced to improve the efficiency of production, thereby yielding coproducts with highly variable composition. Thus, the need for detailed analytical descriptions of newer coproducts is crucial if we expect to fully understand their effects on metabolism and nutrition.

There seems to be no relationship between the addition of ionophores or antibiotics and ruminal H₂S pro-
production in beef cattle fed high-grain diets. The potential toxicity associated with increasing concentrations of S in coproducts remains a challenge, and research efforts should be directed to decreasing ruminal H₂S production, thereby allowing for greater inclusion amounts of coproducts in feedlot diets.

The inclusion of newer coproducts, such as DGS, in feedlot diets has led to a decreased intake of starch and increased intake of NDF relative to a more traditional high-grain finishing diet. As a result, the inclusion of exogenous enzymes, in particular cellulases and xylanases, in diets with an increased quantity of coproducts might hold promise for greater efficiency of coproduct use based on previous in vivo and in vitro studies. The addition of certain probiotics to feedlot diets based on more traditional feed ingredients has sometimes been effective in improving cattle performance; however, as discussed previously, little is known about the possible effects of such probiotics in combination with newer feed ingredients. The possible changes in the ruminal microbial ecosystem exerted by the addition of newer coproducts also requires more research directed at the development of probiotics that improve animal performance under the conditions imposed by newer dietary ingredients.

**LITERATURE CITED**


