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## Fertilizer Potential of Biofuel Byproducts

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### 1. Introduction

Ethanol and biodiesel production have become important industries worldwide. For example, ethanol production in the United States has increased exponentially from 6.0 billion liters in 2000 to 49 billion liters in 2010, an increase of 800% (RFA, 2011). Similarly, biodiesel production increased in the U.S. from 424 million liters in 2005 to 1,191 million liters in 2010 (NBB, 2011). These booming industries have not only changed how we view our automotive fuel, they have also forced us to consider uses for their valuable byproducts. The majority of ethanol produced in the U.S. is through the dry grind process. Dried distillers grains (DDGS) is the predominate byproduct of dry-grind ethanol production. It has been estimated that for every liter of ethanol produced, 3.5 kg of DDGS are left over (Rausch and Belyea, 2006). Based on the production estimates listed above, this would have equated to 34.9 million metric tonnes of dried distillers grain produced in the U.S. in 2010.

Soybean oil and canola oil are the most commonly used vegetable oils for biodiesel production in the U.S. The oil is extracted from soybeans and canola seed through a process of cold-pressing, leaving behind valuable seed meal byproducts. An estimated 80% of soybean seed 60% of canola seed is left from the extraction process as seed meal, creating a significant quantity of this important byproduct (NBB, 2008; Herkes, 2010).

The most common use of DDGS, soybean meal, and canola meal is for animal consumption as animal feed. DDGS, soybean meal, and canola meal contain an estimated 26, 47, and 35% crude protein, respectively, therefore these byproducts are considered highly valuable animal feed sources (Table 1). However, issues including over-saturation of DDGS in animal feed markets, animal feed quality issues, and the extremely high costs associated with oilseed meals has forced some biofuel producers to consider other markets for these byproducts.

A potential market for DDGS and oilseed meals that biofuel producers may consider is the fertilizer/agriculture market. DDGS and oilseed meals are rich in plant macronutrients (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S)) and plant micronutrients (zinc (Zn), iron (Fe), manganese (Mn), and boron (B)). In addition, these materials have a relatively low carbon-N ratios (ranging from 5:1 to 15:1), therefore these materials are highly decomposable and are able to release organic forms of N to plant available forms of N shortly after field application. This property is of particular interest to organic agriculture markets, where nutrient sources and fertilizers containing enough readily mineralizable N to impact yield are scarce.

The purpose of this chapter is to discuss byproducts of ethanol and biodiesel production as effective nutrient sources for plants. Specifically, we will cover 1) how these byproducts are

made, 2) plant nutrient composition of the byproducts, 3) competition with animal feed markets, 4) situations where biofuel byproducts should be considered as a fertilizer, and 5) a review of field and laboratory research studies that investigate the fertilizer value of these byproducts.

## 2. Common byproducts of biofuel production

In this section, we will provide some background information on how biofuel byproducts of greatest interest to growers are generated during the production of ethanol from dry-grind processing and biodiesel from soybean and canola oils.

### 2.1 DDGS from ethanol production

Over the past 15 years, dry-grind corn processing has become the primary method for producing ethanol in the U.S., favored over wet milling and dry milling (Rausch and Belyea, 2006; RFA, 2011). The simplified steps for making ethanol from corn using the dry-grind method are 1) mixing ground grain corn with water, 2) cooking the mixture and adding amylase enzyme, and 3) liquefying the mixture and adding glucoamylase enzyme and yeast for fermentation. The products of fermentation are ethanol, water, and solids. The solids, also referred to as “whole stillage”, are removed from the bottom of the fermentation unit and centrifuged to separate the solids into wet grains and thin stillage. The thin stillage is generally evaporated to form a thick syrup, which is added back to the wet grains. These wet grains are referred to as wet distillers grains with solubles (syrup) added, or WDGS. The final step of this process is to dry the wet grains to form DDGS with solubles (syrup) added, or DDGS (Rausch and Belyea, 2006).



Photo 1. Typical sample of DDGS from ethanol production. Photograph taken by Amber Moore.

## 2.2 Oilseed meals from biodiesel production

The main components used to make biodiesel are soybean or canola oil and an alcohol source, typically methanol. Seed meal byproducts are left after oil is extracted from soybeans and canola oil. While the methods used for extracting oil vary slightly between soybeans and canola seeds, oil is extracted from most oilseeds through a process of cleaning, drying, dehulling, size reduction, flaking, cooking, and tempering (Dunford). The most critical step of this process is cooking/tempering, which is also referred to as conditioning. During this step, oilseeds are cooked or tempered to denature proteins, which releases oil from the seeds and inactivates enzymes. Once they reach a specified temperature, cooked/tempered seeds are pressed to separate oil from the seed. The portion of seed solids remaining after this process is referred to as the meal. The oilseed meal can be used immediately as an animal feed without further treatment.



Photo 2. Typical sample of canola meal from oil-pressed canola seeds. Photograph taken by Amber Moore.

## 3. Plant nutrient composition

As mentioned above, DDGS and oilseed meals are rich in plant macronutrients (N, P, K, Ca, Mg, and S) and plant micronutrients (Zn, Fe, Mn, and B). While all of these nutrients are important for optimal plant growth, N is considered the most critical for all crops. Nitrogen is needed by plants to support vegetative growth and chlorophyll production. Unfortunately, plant available forms of N (ammonium ( $\text{NH}_4\text{-N}$ ) and nitrate ( $\text{NO}_3\text{-N}$ )) are quickly taken up by plants, leached out of the soil root zone, converted to ammonia ( $\text{NH}_3$ ) gas, and/or utilized by soil microbes, therefore plant available forms of N do not usually stay in the soil for longer than a single growing season. Also, many organic waste products, such as compost and cattle manure, contain relatively low concentrations of N that may take several years to be converted by microbes to forms that can be used by the plant.



Fortunately, most biofuel byproducts contain high enough concentrations of N to be rapidly available for plant use within the first growing season after application. To quickly and roughly estimate PAN from organic amendments based on total N content, the equation that supports the Oregon State University Organic Fertilizer calculator can be used (Sullivan et al., 2010). To predict full-season PAN for organic materials with less than 6% total N, the calculator uses the equation  $\%PAN = ((-30 + 15 * (\text{fertilizer total N}\%)) + 15\%)$ . To predict full-season PAN for organic materials with more than 6% total N, the calculator estimates 75% PAN. Applying the value averages from Table 2 and the OSU Organic Fertilizer Calculator, PAN estimates over a growing season for most climates and soils are 50% for DDGS, 75% for soybean meal, 70% for canola meal, and 71% for mustard meals, all varieties. Based on these estimates, the availability of N from biofuel byproducts is only slightly less than most chemical N fertilizers, which are assumed to be 90-100% plant available shortly after application. In this case, it is possible that conventional and organic growers could grow plants near or at optimal yields based on chemical N fertilizer applications.

In addition to N, P and K content of biofuel byproducts is also of great value to growers. As reported by Nelson et al. (2009), the N:P of the DDGS used in the study (5.5:1) was comparable to corn uptake ratios (5.9:1), suggesting that DDGS and other biofuel byproducts with similar N:P ratios could meet both the N and P needs of a crop when applied on a N basis without over- or under-applying P. In 2008, many U.S. growers were unable to afford P or K chemical fertilizers. Based on values listed in table 2, biofuel byproducts may be a viable option for these growers in the future if and when P and K fertilizer prices increase beyond what a grower can afford to pay.

With the addition of a wide variety of other plant macronutrients and micronutrients, biofuel byproducts have the potential to be an all-purpose fertilizer for many growers.

#### 4. Competition with use as animal feeds

While the concept of using oilseed meals as a fertilizer is a relatively new one in the U.S., growers in Asia have widely considered rapeseed oil cake as a viable fertilizer source for over 40 years (Abe et al., 2010; Chen and Hsieh, 1972; Kora and Shingte, 1988; Singh and Gurumurt, 1984). The primary reason why biofuel byproducts are not widely used for fertilizer applications is competition with the animal feed industry. DDGS and many oilseed meals hold more value as an animal feed than as a fertilizer source, therefore animal producers are willing to pay for materials based on feed value instead of the lower fertilizer value. For example, one economic analysis showed that feed value of DDGS exceeded the fertilizer value by an estimate \$99 tonne<sup>-1</sup> (Lory et al., 2008). Using the U.S. price values of 2007 for anhydrous ammonia, diammonium phosphate (DAP), and potassium chloride (KCl) and total nutrient estimates of 50 g N kg<sup>-1</sup>, 8.6 g P kg<sup>-1</sup>, and 12.1 g K kg<sup>-1</sup> for DDGS, Lory et al. (2008) estimated that the theoretical fertilizer value of the DDGS was \$39 tonne<sup>-1</sup>, in comparison to the 2007 U.S. animal feed value for DDGS of \$172 tonne<sup>-1</sup>. Similar cost comparisons likely exist for soybean and canola meal. At these rates, conventional growers would have a difficult time justifying paying feed value costs for a fertilizer source, which far exceed the value of widely available chemical fertilizers. In addition, ethanol and vegetable oil producers would have an equally difficult challenge in lowering prices to accommodate grower needs.

Material	C:N	Mois ture	N	P	K	Ca	Mg	S	Fe	Mn	Zn	B	Cu	Na	Reference
-----g kg <sup>-1</sup> -----mg kg <sup>-1</sup> -----															
DDGS	12.0	---	41	3	4	0	0.9	0.4	104	6	20	15	2	---	Moore et al., 2010
	---	111	48.3*	8.9	9.4	6	3.3	4.7	119.8	15.8	97.5	---	5.9	2400	Spiehs et al., 2002
	---	108	41.5*	8.2	10.4	2.4	3.2	5.7	74.5	13.7	58.0	---	4.6	1700	Shurson, 2010
	---	102	38.2	6.9	11.5	---	---	---	87.0	18.8	78.3	---	6.5	---	Nelson et al., 2009
Soybean meal	5.1	---	64.3	---	---	---	---	---	---	---	---	---	---	---	Rubins and Bear, 1942
	5.4	109	87	---	---	---	---	---	---	---	---	---	---	---	Van Kessel et al., 2000
Canola meal (B. napus)	7.6	---	63	14	15	4.2	4.4	7	---	---	---	---	---	---	Snyder et al., 2010
	8.0	25	56.6	---	---	---	---	---	---	---	---	---	---	---	Gale et al., 2006
	---	---	51	6.63	7.75	6.4	2.9	4.7	186	41	31	36	5	---	Banuelos and Hanson, 2010
Mustard meal (B. carinata)	14.4	---	61	6	11	---	---	6.0	---	---	---	---	---	---	Balesh et al., 2005
Mustard meal (Sinapis alba)	8.5	---	58	3	3	1	1.2	0.4	54	8	23	15	1	---	Moore et al., 2010
	8.4	---	58	13	10	4.8	3.8	18	---	---	---	---	---	---	Snyder et al., 2010
	---	---	49	9.62	10.9	7.7	3.7	12.6	313	32	49	49	9	---	Banuelos and Hanson, 2010
Mustard meal (B. juncea)	7.8	---	62	13	10	4.3	5.0	18	---	---	---	---	---	---	Snyder et al., 2010
1															

\*Based on crude protein value, assume that protein is 16% N

Table 1. Total plant nutrient content and C:N ration of various biofuel byproducts.

5. When to consider biofuel byproducts as a fertilizer source

While competition with the animal feed industry has made it difficult for biofuel byproducts to gain recognition as a viable fertilizer source, there are several factors that may cause biofuel producers to consider applications as fertilizers for their byproducts.

5.1 Advantages of DDGS in fertilizer markets

5.1.1 Feed market value of DDGS

One concern is that DDGS supply will increase beyond the demand that currently exists for this material as animal feed. In the last three years, ethanol producers have avoided hitting the “feed wall” by exporting DDGS to countries like China, Mexico, and Canada (RFA, 2011). In 2010, DDGS exports from the U.S. were an estimated 8 million metric tons, which is almost 25% of all distillers grain produced in the U.S. (RFA, 2011). While exports have helped producers find markets for the time being, the ethanol industry will have no choice but to reach out to other markets, such as fertilizer markets, if ethanol production continues to increase at its current rate.

Another economic issue for using DDGS as animal feed is competition with other feeds (Table 2). Dietary ingredients are generally the single largest expense in animal production. In addition to DDGS, animal producers select from a wide variety of other products, including corn grain, cottonseed meal, and rice meal. For example, due to a higher protein content, DDGS is typically more expensive than corn. Producers will naturally prefer the most economic dietary ingredients, which can put additional pressure on marketing ethanol products.

Feed source	Price (\$/tonne)
Alfalfa meal	229
Cottonseed meal	284
DDGS	204
Rice bran	146
Soybean meal	396
Wheat bran	159

Table 2. U.S. byproduct feed prices for February, 2011. Source: ERS, 2011.

5.1.2 Animal feed consumption issues with DDGS

There are a wide variety of concerns for using DDGS as an animal feed source. One of the biggest concerns is the high P concentrations of the grains (Morse et al., 1992). Phosphorus contents of DDGS range between 5.4 and 8.2 g kg<sup>-1</sup>, which exceeds the nutritional requirements of most ruminants, and is also high in comparison to corn grains (NRC, 1980). Excess P in the diet is excreted as manure, which is usually land-applied for disposal. From here, the P can be transported via water and wind to nearby waterways, polluting the waters by stimulating excessive algal growth, depleting dissolved oxygen levels, thus negatively impacting aquatic plant and animal species. It is possible that some animal producers will not purchase high P feeds, such as DDGS, due to a lack of manure disposal options.

Another issue that producers face is the variability in the nutritional composition of DDGS. It has been estimated that protein content can vary as much as 25-35% from one batch to the next (Belyea et al., 1989). Mineral inconsistencies have also been documented (Arosemena et al., 1995; Belyea et al., 2004). Miscalculations of proteins and mineral content in feed could affect the quality of animal products and animal health.

Other concerns animal consumption issues with DDGS include difficult digestibility due to high fiber content (Rausch and Belyea, 2006), stimulation of thiamine deficiencies due to high sulfur content (Rausch and Belyea, 2006), and carcinogenic aflatoxins concentrated in DDGS from tainted corn grain (Blanco-Canqui et al., 2002).

### 5.1.3 Organic markets for DDGS

In recent years, organic growers in the U.S. have been showing increased interest in using DDGS as a possible fertilizer source for organic production. With low C:N ratios and typical N content ranging between 3.8 and 4.8% N, DDGS is a promising option as a N fertilizer source. This is critical for organic producers, who have limited options for affordable organically certified N fertilizer sources. Nitrogen is generally the most limiting nutrient for plant growth, and therefore can have the greatest impact of all of the plant nutrients on crop yield and quality. Organic N fertilizer sources are generally limited to raw animal manures, composted animal manures, and leguminous and non-leguminous cover crops. While raw animal manures like poultry litter and swine manure can feasibly meet the N requirements of most crops, issues arise with limited availability to specific regions, timing limitations on using raw manures for organic crops, and non-acceptance by some growers and international markets of raw manures as an organically certified practice.

Another reason why organic growers may be interested in DDGS is the potential for weed suppression. A small number of studies have identified weed suppression characteristics in DDGS, although the mechanism is poorly understood at this time (Boydston et al., 2007; Liu and Christians, 1994). While it has been shown to be only a mildly effective herbicide, organic growers may still be interested in these properties since options for certified organic herbicides are extremely limited.

The approval of using DDGS as a certified organic fertilizer source in the U.S. has been somewhat controversial in recent years. The two major issues have been the approval of corn steep liquor (CSL) and the addition of antibiotics to DDGS. Corn steep liquor is a byproduct of the wet milling process, which differs from the dry-grind process used to produce DDGS. However, the approval of DDGS by individual state organic regulatory agencies has often been directly linked to the approval of CSL. After extensive debate, the Organic Materials Review Institute (OMRI) announced on January 13, 2011 that they would continue to treat CSL as an allowed non-synthetic ingredient for the purpose of product review (OMRI, 2011a). However, it is possible that this ruling could be overturned, so it is advised that organic growers stay up to date with their country's approval of CSL when considering DDGS field applications.

The other concern with using DDGS as an organic certified fertilizer source is the addition of antibiotics to the grains. Antibiotics are often added by ethanol producers during the fermentation process to destroy unwanted bacteria, leaving small concentrations of antibiotic residues in the DDGS. While this does occur, the use of antibiotics in agriculture is difficult to avoid. Antibiotic residues may also be found in manure and compost materials, however the use of antibiotics in animals whose manures are used for organic agriculture is not regulated in the U.S. It should be noted that there is no clear rule that prohibits the use



of DDGS containing trace residues of antibiotics as fertilizers. As with this and any other organic practice, we strongly recommend consulting your local organic certifier before using DDGS or any questionable fertilizer amendment.

## 5.2 Advantages of oilseed meals in fertilizer markets

One concern in using oilseeds as animal feed is cost. As listed in Table 1, soybean meal is 1.9 times greater in cost than DDGS, 2.5 greater than wheat bran, and 2.7 times greater than rice bran. As mentioned above, animal feed accounts for the greatest in any animal operation, therefore animal producers are likely to choose the most economical option for their operation.

Similar to DDGS, the high N concentration and plant N availability of oilseed meals is appealing to organic growers who have limited options for fertilizer N sources. Most oilseed meals are currently approved by OMRI for use as an organic fertilizer in the U.S. as “uncomposted plant materials) NOP standard 205.203(c)(3) (NOP, 2011). Soybean meal is currently listed in the Generic Materials List as an allowed Crop Fertilizer and Soil Amendment (OMRI, 2011b). While canola meal, mustard meal, and other oilseed meals are not listed, products containing canola meal and mustard meal are listed under the OMRI materials database. Oilseed meals do not have the approval issues associated with DDGS because the pressing process used for extracting oils from the oilseeds is fairly simple and does not require the addition of chemical solvents or antibiotics during processing. Again, we recommend working with your organic certifier before using oilseed meals as a fertilizer source, even though they are generally approved as an organic fertilizer source. For example, individual certifiers may have concerns if the seeds used were genetically modified organism (GMO).

Mustard meal has unique properties that make it a favorable fertilizer and even herbicide source, yet a very poor option as an animal feed. Mustard meal is considered harmful to animals as a feed source due to high concentrations of erucic acid and glucosinilates (Joseffson, 1970). However, the presence of glucosinilates, which break down to isothiocyanates, can be beneficial for a wide variety of pesticide applications. Mustard seed meals have been shown to control weeds (Boydston et al., 2007; Norsworthy and Meehan, 2005; Rice et al., 2007; Vaughn et al., 2006), insect pests (Elberson et al., 1996, 1997); nematodes (Walker, 1996; Walker, 1997), and pathogens (Chung et al., 2002; Mazzola et al., 2007). Organic markets have taken interest in the pesticide properties of mustard seed meals, especially since effective organically certified pesticide option are limited. Organic growers can therefore benefit from both fertilizer and pesticide benefits of mustard meals. However, growers must be careful of applying the mustard meals too close to planting. Mustard meals can be non-discriminate and can burn emerging crop plants if not enough time is allowed for the isothiocyanate compounds to break down in the soil.

## 6. Biofuel byproducts as fertilizers – research efforts

As described above, the high N content (38 – 87 g N kg<sup>-1</sup>) and low C:N ratio (5.1 – 12.0) strongly suggest that biofuel byproducts are effective N fertilizer sources (Table 1). Nitrogen mineralization studies are commonly used to closely determine plant available N (PAN) in organic amendments, such as biofuel byproducts, as opposed to roughly estimating PAN based on C:N and N content. These studies can account for influences from the organic

amendment on the soil microbial populations that convert organic N to plant available forms of N ( $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$ ) unrelated to N content.

One of the most common methods for measuring N mineralization is to monitor changes in  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  concentrations in a soil amended with a specific organic material over time. PAN measurements listed in Table 3 for various biofuel byproducts all fall in this category (Moore et al. 2010; Rubins and Bear, 1942; Van Kessel et al., 2000; and Gale et al., 2006). Another method for measuring N mineralization is to use  $^{15}\text{N}$  labeling, where the N in the organic amendment is labeled with the rare  $^{15}\text{N}$  isotope, and the changes in concentration of  $^{15}\text{NH}_4\text{-N}$  and  $^{15}\text{NO}_3\text{-N}$  are monitored. This method was used by Snyder et al. (2010) to determine PAN for canola and mustard meals (Table 3). While these methods do differ, the PAN estimates are generally comparable to each other.

Based on N mineralization incubation studies with biofuel byproducts using methods described above, N appears to be quickly available to plants from soybean meal and canola meal sources. Reviewing N mineralization studies of canola meal and soybean incubated at various soil types and incubation temperatures, N mineralization patterns were relatively consistent among studies. These studies showed that between 93 and 100% of N added as either canola meal or soybean meal was in the plant available forms ( $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$ ) in the first 28 days of the 40-112 day incubation periods (Table 3) (Rubins and Bear, 1942; Van Kessel et al., 2000; Gale et al. 2006; Snyder et al., 2010). These findings suggest that soybean and canola meal would be excellent as preplant N fertilizer sources, especially for crops able to utilize N within the first month or two of growth. Although both would be considered excellent N sources, soybean meal appears to have at least 20% greater PAN values than canola meal (Table 3). This difference can easily be attributed to the lower C:N (4.7-5.4 for soybean meal compared to 7.8 – 8.0 canola meal) and higher concentrations of N (76-87 g N  $\text{kg}^{-1}$  for soybean meal compared to 57-63 g N  $\text{kg}^{-1}$  for canola meal).

In contrast to soybean and canola meal, research studies suggest that N from DDGS and mustard meal mineralizes somewhat slowly over a growing season. This effect is not caused by N content, especially for mustard meal, which has a comparable N content of 58 g N  $\text{kg}^{-1}$  compared to canola meal, which has a N content of 57-63 g N  $\text{kg}^{-1}$  (Moore et al, 2010; Gale et al., 2006; Snyder et al., 2010). For example, Moore et al. (2010) found that only 56% of N released from DDGS over a growing season was plant available within the first 28 days. The authors speculated that the mild weed-suppressing chemical compounds in DDGS may also suppress nitrifying bacteria populations, although this effect has not been investigated. Similar trends have been seen with mustard meal applications, with two studies showing that a range of 55-82% N released from mustard meal over a growing season was plant available within the first 28 days (Table 3) (Moore et al., 2010; Snyder et al. 2010). Snyder et al. (2010) also recorded a 25% decrease in PAN between day 15 and 45 for *Sinapis alba* mustard meal, attributing the decrease to a delayed release of isothiocyanate from glucosinilates in the mustard meal.

The effect of mustard meal on nitrifying bacteria populations is better understood than DDGS. Bending and Lincoln (2000) discovered that isothiocyanate compounds found in mustard seed both reduced populations and inhibited the growth of nitrifying bacteria. Snyder et al. (2009) also showed that microbial biomass N concentrations for two varieties of mustard meal treatments (*Brassica juncea* and *Sinapis alba*) were 48 and 67% lower than for canola meal treatments, which the authors attributed to the biocidal properties of the isothiocyanate compounds in the mustard meal. The slow-release N characteristics of DDGS and mustard meal are beneficial for plant growth, supplying N throughout a growing

season when the plant is most likely to use it. When all of the N is in plant available form early in the season, as is the case for most mineral N fertilizers, what is not taken up by plants is quickly leached out of the soil and therefore no longer available for plant uptake.

Amendment	C:N	Total N	PAN (8-14 days)	PAN (15-28 days)	PAN (29-56 days)	PAN (57-126 days)	Reference
		g kg <sup>-1</sup>	-----%-----				
			--				
DDGS	12	41	17	31	46	55	Moore et al., 2010
Soybean meal	4.7	76	-----	61	65	-----	Rubins and Bear, 1942
	5.4	87	46	62	62	64	Van Kessel et al., 2000
Canola meal	8	57	39	-----	39	41	Gale et al., 2006
	7.6	63	-----	42.5	42.5	-----	Snyder et al., 2010
Mustard meal (S. alba)	8.5	58	17	33	49	60	Moore et al., 2010
	8.4	58	-----	45.8	34.1	-----	Snyder et al., 2010
Mustard meal (B. juncea)	7.8	62	-----	40.5	49.3	-----	Snyder et al., 2010

Table 3. Plant available N (PAN) estimates from the total N pool for various biofuel byproducts.

The majority of peer-reviewed field research conducted has illustrated yield increases with increased rates of biofuel byproducts. Nelson et al. (2009) investigated three field application rates of DDGS in comparison to a slow-release poly coated urea (PCU) and anhydrous ammonia on a corn grain crop. Using application rates of 0, 1.2, 2.4, and 3.6 tonne DDGS ha<sup>-1</sup> (or 0, 46, 92, and 138 kg N ha<sup>-1</sup>), Nelson et al. (2009) showed a grain yield increase of 1.41 and 1.56 kg grain ha<sup>-1</sup> for every kg ha<sup>-1</sup> of DDGS applied in medium and high yielding environments. Balesh et al. (2005) applied mustard meals as a fertilizer for tef at three application rates of 0.24, 0.38, and 0.51 tonne meal ha<sup>-1</sup> (or 15, 23, and 31 kg N ha<sup>-1</sup>). Over the three rates and two years of field research, Balesh et al. (2005) showed that tef grain yield increases ranged from 2 to 116% in comparison to control treatments that did not receive any N applications. At the highest rate (31 kg N ha<sup>-1</sup>), tef grain yields at least doubled in comparison to the control in both years, and were comparable to the Ethiopian national tef production average of 800 kg ha<sup>-1</sup>. These finding suggests that mustard meal may be used as a viable substitute for chemical fertilizers in tef production. Balesh et al. (2005) also found that a decreased particle size of mustard meal increased yields, with mustard meal powder

applications increasing yields by 39 and 5% in 1994 and 1995, respectively. It should be mentioned that the authors applied mustard meals 20 days prior to planting to avoid toxicity issues with the germinating seed (Balesh et al., 2005). Banuelos and Hanson (2010) studied the application of selenium-enriched mustard and canola meals to strawberries. In this study, fruit yields increased at both rates of canola meal application (4.5 and 13.4 tonne acre<sup>-1</sup>, or 230 and 683 kg N ha<sup>-1</sup>) and at two of the three rates of mustard meal applications (2.2 and 4.5 tonne ha<sup>-1</sup>, or 108 and 220 kg N ha<sup>-1</sup>). An increase in Ca, P, and Mn concentrations in the fruit was observed for canola and mustard meal applications. Over both years, the authors noted that strawberry plants transplanted shortly after mustard meal applications were initially stunted and discolored; however, strawberry survival, growth, and productivity were similar among all treatments. These three studies clearly illustrate that biofuel byproducts can significantly improve crop yields.

Addressing the potential for plant toxicity with mustard meal applications, there are a few studies that have illustrated negative impacts on plant growth with increasing application rates. Snyder et al. (2009) found that mustard meal applications of 1 and 2 tonne ha<sup>-1</sup> (or approximately 59 and 118 kg N ha<sup>-1</sup>) applied 36 days prior to planting did not affect emergence, while applying the *Sinapis alba* mustard meal only 15 days prior to planting decreased emergence up to 40%. Regardless, total fresh market yield was either comparable to or greater than the control for both years of the two-year study. Strawberry yields decreased by 42% compared to the control treatment when mustard meal was applied at rates of 13.4 tonne acre<sup>-1</sup> (Banuelos and Hanson, 2010). In both studies, the authors attribute the decrease in plant growth to glucosinilates in the mustard meals. When in contact with water, the glucosinilates break down to form isothiocyanates, which is a known plant growth suppressant.

## 7. Conclusion

DDGS byproducts of ethanol production and oilseed meal byproducts of biodiesel production can be effective fertilizer sources for plants. In addition to containing most macronutrients and micronutrients needed to support plant growth, these byproducts have low C:N ratios, which means that they are rapidly decomposable and can release nutrients to plants in a timely manner. Competition with animal feed markets has prevented widespread adoption of biofuel byproducts as fertilizers. However, fertilizer markets may become more appealing to biofuel producers due to over-production of DDGS, high costs of oilseed meals, DDGS feed quality issues, and interest from organic growers in alternative nutrient-rich fertilizer sources. Research studies have illustrated that biofuel byproducts can be used as effective fertilizer sources, although growers working with mustard meals should be cautioned to allow enough time to pass between application and planting for phytotoxic glucosinilates to lose their potency. If and when the time ever comes when biofuel byproducts can compete with animal feeds as an economically viable fertilizer source, they will provide a much needed competitive fertilizer source to chemical fertilizers for conventional growers, and will help to produce yields for organic crops comparable to those seen for conventional crops.

## 8. Acknowledgements

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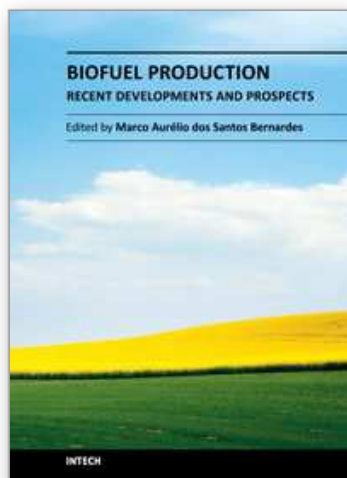
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