Nutrient cycling in the vegetable processing industry: Utilization of potato by-products

E. Charmley[1, 4], D. Nelson[2], and F. Zvomuya[3]

[1]*Crops and Livestock Research Centre, Agriculture and Agri-Food Canada, Nappan, Nova Scotia, Canada B0L 1C0 (e-mail: ed.charmley@csiro.au), [2]Soiltest Farm Consultants, Inc., Moses Lake, WA 98837-4517, USA; and [3]Agriculture and Agri-Food Canada, Research Centre, Lethbridge, Alberta, Canada T1J 4B1.*

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Charmley E., Nelson, D. and Zvomuya, F. 2006. **Nutrient cycling in the vegetable processing industry: Utilization of potato by-products.** Can. J. Soil Sci. **86**: 621–629. Potato (*Solanum tuberosum*) production in Canada and the United States totals approximately 30×10^6 Mg yr^{-1}. Approximately half of this is unsuitable for human consumption. This potato by-product comprises cull potatoes and potato processing waste (PPW). Liquid waste from processing plants can be applied to agricultural land. With strict environmental monitoring and control, crops such as corn (*Zea mays* L.), vegetables and grass can be used to divert large volumes of liquid waste. Solid waste and culls have traditionally been put in landfills or disposed of on agricultural land as a fertilizer. However these can be diverted from landfill sites or agricultural land and used as a high-quality animal feed, principally in beef feedlots. Research has shown that PPW can replace corn and barley (*Hordeum vulgare* L.) grain without negative effects on growth of beef cattle or meat quality. Indeed, efficiency of animal growth per unit diet intake is improved. These effects have been observed with diets containing up to 80% PPW. Results to date suggest that PPW is a valuable livestock feed ingredient and has no deleterious effects on beef quality. In areas where PPW is available, feeding to beef cattle represents a viable alternative to other disposal options.

Key words: Potato, processing waste, by-product, cattle, land disposal

Charmley, E., Nelson, D. et Zvomuya, F. 2006. **Le cycle des éléments nutritifs dans l’industrie de transformation des légumes : utilisation des sous-produits de la pomme de terre**. Can. J. Soil Sci. **86**: 621–629. La culture de la pomme de terre (*Solanum tuberosum*) totalise environ 30×10^6 Mg par année aux États-Unis et au Canada. Environ la moitié de cette masse est impropre à la consommation humaine. Les sous-produits comprennent les tubercules de réforme et les déchets de transformation. Les résidus liquides issus des usines de transformation peuvent être épandus sur les terres arables. Les cultures comme le maïs (*Zea mays* L.), les légumes et les graminées peuvent servir à détourner une grande quantité de ces résidus pourvu que la surveillance de l’environnement et la réglementation soient assez sévères. D’habitude, on se débarrasse des déchets solides et des tubercules de réforme dans les décharges publiques ou on s’en sert pour bonifier les terres agricoles. Cependant, il arrive qu’on les utilise comme aliment du bétail de qualité, principalement pour nourrir les bovins de boucherie. Les recherches indiquent que les déchets de transformation de la pomme de terre peuvent remplacer le maïs et l’orge (*Hordeum vulgare* L.) sans incidence négative sur la croissance des bovins ou la qualité de la viande. De fait, on note une amélioration de la croissance de l’animal par unité d’aliment ingérée. Ces résultats ont été observés avec des rations contenant jusqu’à 80 % de résidus de transformation de la pomme de terre. Jusqu’à présent, les résultats laissent croire que les déchets de transformation de la pomme de terre sont un ingrédient utile pour l’alimentation des animaux et ne détériorent pas la qualité du bœuf. Là où on en trouve, donner de tels sous-produits aux bovins de boucherie constituerait une solution de rechange viable aux autres méthodes d’élimination.

Mots clés: Pomme de terre, déchets de transformation, sous-produit, bovins, dépôt en milieu terrestre

During the past 20 yr, potato (*Solanum tuberosum*) production in Canada has increased from 2.5 to over 4×10^6 Mg yr^{-1} (Prince Edward Island Department of Agriculture and Forestry 2005; Statistics Canada 2005), with much of this increased production destined for processed potato products such as french fries and chips. Today, over 50% of potatoes in Canada are destined for value-added processing. Farm gate receipts for potato production in Canada now account for over $700 million annually (Prince Edward Island Department of Agriculture and Forestry 2005; Statistics Canada 2005). It is estimated that approximately 40 to 50% of potato production is unsuitable for human consumption. This potato by-product can be divided into two major types: cull potatoes, which are whole potatoes not destined for human consumption or seed, and potato processing waste (PPW), derived from the manufacture of potato-based food products. Partial de-watering of waste streams also results in production of liquid waste, which can be applied to the land.

Although accurate statistics are difficult to obtain, it is apparent that about 2×10^6 Mg of potato by-product (culls and PPW) are produced annually in Canada. This by-product can be returned to the land as fertilizer, for example in times of excess supply, dumped in landfill sites or fed to livestock. In recent years, new potato processing practices have resulted in a greater proportion of potatoes being used for human consumption. Dehydration of small, large or misshapen potatoes is being employed in the production of high-value reconstituted potato chips. There is increasing

Abbreviations: **BW**, body weight; **DM**, dry matter; **MPCA**, Minnesota Pollution Control Agency; **POTW**, publically-owned treatment works; **PPW**, potato processing waste; **WSDOE**, Washington State Department of Ecology

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[4] *Present address: CSIRO Livestock Industries, P.O. Box 5545, Rockhampton Mail Centre, Qld. 4702, Australia.*

interest in adding value to potato wastes, but this remains experimental in nature. For example the starch can be used as a substrate for producing lactic acid (Liu 2005). Nevertheless, high volumes of potato waste will continue to be produced in localized areas of Canada.

In Prince Edward Island, approximately 500 000 Mg of potato by-product is produced annually (L. J. Halliday, personal communication). Table 1 defines the various types of potato by-product and Table 2 details the approximate volumes of the different waste streams. Potato by-product in Prince Edward Island represents about 20 to 25% of Canadian production and is representative of that produced in other parts of Canada.

The potato industry in the United States follows a pattern similar to that found in Canada. In 2002, the total potato production was approximately 25×10^6 Mg yr^{-1} (USDA Economic Research Service 2004). Of the 86% of the potatoes destined for human consumption, 57% or 14×10^6 Mg were processed in some way and 29% went to fresh consumption. Although no specific data are available from the processing industry, it is generally estimated that 50% of the potatoes sent to processing end up as saleable product. The remaining 50% become some form of waste or by-product. The actual product recovery varies considerably in response to processing technology, market demands, disease and weather conditions. Thus, in the United States approximately 7.2×10^6 Mg of potato waste is typically produced annually.

In the state of Washington, virtually all potatoes grown for processing are raised in the Columbia Basin of the south-central part of the state. Approximately 4.3×10^6 Mg yr^{-1} of potatoes (85% of total production) entered the processing stream in 2002. Of the 50% going to human consumption, 59% were fries or formed potato products, 20% were chips, 20% were dehydrated and 1% were canned or used as starch. The remaining 50%, nearly 2×10^6 Mg yr^{-1}, ended up as "waste" (USDA National Agricultural Statistics Service 2003; Washington State Potato Commission, personal communication).

Since such a large proportion of potatoes is not used for human consumption, it follows that the cycling of waste nutrients has evolved into highly developed processes. This review focuses on two areas: the application of vegetable processing plant waste water to agricultural land and the feeding of potato waste to ruminants.

LAND APPLICATION OF POTATO PROCESSING WASTE

The potato processing industry generates large volumes of waste, mostly for non-consumptive purposes. Typically, 8-28×10^3 L of wastewater are generated per metric ton of raw potatoes processed (Council for Agricultural Science and Technology 1995). The raw potatoes entering a processing facility are typically 20% solids and 80% water. Additional water is commonly added for washing, conveying the product within the processing plant, cooking or other processes. The waste streams are managed and treated so that the liquid and solid wastes are separated. Liquid PPW can then be treated on-site, discharged to a publicly owned treatment works (POTW), or recycled through land application. Because of the large volumes of waste requiring treatment, the increasingly strict discharge regulations and the escalating costs of tertiary treatment, land application has become a common practice. Land application is a beneficial reuse of PPW, which typically costs 30 to 50% less to operate than conventional mechanical treatment options (Uhlman and Burgard 2001) and can be used to supplement or even bypass the energy-intensive conventional treatment methods. To optimize economic viability and environmental benefits, land application of wastewater necessitates the production of a marketable crop to provide a mechanism for the removal of nitrogen (N), phosphorus (P) and other nutrients from receiving soils (Uhlman and Burgard 2001; US Environmental Protection Agency 2004). With total N concentrations exceeding 150 mg L^{-1} (Burgoon et al. 1999; Zvomuya et al. 2006a) and total P concentrations in excess of 72 mg L^{-1} in PPW and 300 mg $^{-1}$ in potato processing sludge, PPW applications on cropland can match or even exceed N and P requirements of most agricultural and forage crops (Zvomuya et al. 2006a). Nutrients from the wastewater are added in small doses, thus making highly mobile nutrients, particularly N, less susceptible to leaching and their utilization more efficient.

Land treatment of PPW in Washington State is under the authority of the Washington State Department of Ecology (WSDOE). A rigorous permitting process is required, which includes monitoring of PPW quality and quantity factors, soil tests, crop harvest removals, application rates and various other conditions (WSDOE 1993). Depending on the situation, PPW is applied to land owned by the processor and/or to nearby land owned by a grower/co-operator through some arrangement approved by WSDOE.

Loading Rates

In the early years, PPW loading rates were dependent on the production of the plant and the area of the most convenient field. As a consequence, hydraulic and nutrient loading rates were frequently very high. Nitrogen loading rates frequently exceeded 1000 kg ha^{-1} (Smith 1976; Smith et al. 1976). The earlier land application systems emphasized cheap waste disposal with little attention to environmental protection, and aimed at maximizing the amount of waste applied per unit land area rather than the beneficial use of waste as a source of nutrients and water for plants (Bastian 2005).

With the increasing concern over ground- and surface water quality in recent years, these earlier practices have evolved to closely managed systems that allow for the beneficial reuse of nutrients and water while effectively treating the wastes (Bastian 2005). Accordingly, the permitting processes for land application have required that PPW application rates are calculated based on hydraulic loading, nutrient loading and/or salt loading. The nature of the PPW and the land to which it is applied determines which components are monitored the closest to determine application limits. In addition, land application permits, such as those issued by the WSDOE, generally require that sufficient fresh water is available at the land application site to meet 75% of the crop needs so that the PPW will be applied at a rate no greater than 25% of the total water requirement. Hydraulic loading

Table 1. Descriptions of culls and potato processing waste produced in eastern Canada

Name	Description
Cull potatoes	Whole or parts of unprocessed potatoes discarded from the human food line due to imperfections, or whole potatoes not sold off the farm due to oversupply, trade restrictions, etc.
Potato processing waste (PPW)	
Potato steam peel	Potato peel removed from the raw potato by heating the potatoes with high-pressure steam. It is a sticky product with the consistency of peanut butter.
French fry waste	Processed french fries not suitable for human consumption. The product is high in fat and may contain high levels of seasoning.
Dried potato meal	Combination of by-products generated by potato processing. The waste is dried and sold as a high value energy feed.
Filter cake or gray starch	Sludge from settling tanks, comprised of free starch and small potato pieces

Table 2. Components of potato by-product in Prince Edward Island

	% of total processing by-product	By-product (Mg, fresh basis)	Added components[z] (Mg)	Total (Mg, fresh basis)
Total processing by-product				405 000
Steam peel	30	81 000	81 000	162 000
Dry waste	20	64 000	16 000	80 000
French fries	35	114 000	0	114 000
Gray starch	15	49 000	0	49 000
Cull potatoes		82 000		82 000
Total potato by-product				487 000

[z] This includes water or ingredients such as fat, oil, flavourings, etc.

from PPW is generally of greatest concern during the winter when rainfall is highest and evapotranspiration (ET) is lowest and freezing conditions occur. Land application permits frequently preclude land application during winter months when freezing temperatures are likely. During this time lined storage lagoons are commonly used. Land application managers utilize professional soil scientists to provide soil monitoring, irrigation scheduling and management planning (WSDOE 1993).

The rate of application of PPW can be controlled by nutrient or salt loading limitations. The allowable loading rate depends on the nutrient and salt concentrations in the process water, the amount of process water available, the land resources available, and the crops grown. Sometimes, the land application permit will have specific language setting the limits for the concentration of certain salts in the PPW. The effectiveness of the management strategy employed is verified by periodic soil monitoring, usually to a depth of 1.85 m.

In Minnesota, land application of PPW is regulated by the Minnesota Pollution Control Agency (MPCA). During the growing season (April through September), the PPW can be land-applied based on crop N requirements as recommended by the University of Minnesota Extension Service (Rehm et al. 1995). Because soils in the state are frozen during the cold winter months and there are no actively growing crops to take up nutrients from PPW, potato processing facilities operating year-round usually have to choose between discharging through nearby POTWs or storing the PPW for land application during the crop growing season. However, the high surcharges imposed by the municipalities and the cost of constructing enough lagoons for winter storage (up to 6 mo) make both options extremely expensive, particularly for facilities generating large volumes of PPW.

As an alternative, the MPCA currently issues temporary permits allowing application of tertiary treated wastewater on sprayfields that are bermed to prevent runoff to nearby surface water bodies. To protect groundwater, which commonly supplies trout streams in parts of the state, the winter permits require that nutrient concentrations in wastewater applied in the sprayfields during the winter (October through March) must not exceed 6 mg total P L^{-1}, 10 mg nitrate (NO_3) N L^{-1} and 20 mg total Kjeldahl N L^{-1} (Zvomuya et al. 2005). Nutrient loadings of 30–70 kg N ha^{-1} and 7–15 kg P ha^{-1} from winter application of tertiary treated wastewater in sprayfields under reed canarygrass (*Phalaris arundinacea* L.) have recently been documented (Zvomuya et al. 2006a). By comparison, N and P loadings from growing season PPW (wastewater plus sludge) applications averaged 218 kg ha^{-1} and 243 kg ha^{-1} per growing season, respectively, in sprayfields that were cropped to alfalfa (*Medicago sativa* L.) (Zvomuya et al. 2006a). Eighty percent of the N added during the growing season originated from potato processing sludge, and nearly two-thirds of the N applied was organic. Similarly, sludge accounted for 85% of growing season P addition, most of which was tied up by alum [$Al_2(SO_4)_3 \cdot 14H_2O$], added at the on-site wastewater treatment facility.

The PPW is commonly applied by means of center pivot irrigation systems. Wheel lines or solid set sprinklers are also used. Surface irrigation and drip systems are used less often due to poor application uniformity and plugging problems, respectively.

Crops vary in their capacity to treat process wastewater. Forage crops, such as hay or silage corn, are best as they produce the greatest amount of biomass and, consequently, remove more nutrients and salts from the field. For example, alfalfa in the Columbia Basin of Washington produces 18 Mg ha^{-1} of hay in a season, which removes over 520 kg N ha^{-1} (at 20% protein), 450 kg K ha^{-1}, 27 kg Na ha^{-1}, and 1656 kg ha^{-1} total salts (National Research Council 1996). Lower yields in some northern tier states such as Minnesota, however, may result in as little as 125 kg N ha^{-1} being taken up annually by an alfalfa crop (Zvomuya et al. 2006a). Potatoes are also very effective at removing N and potassium (K). A typical yield of 67 Mg ha^{-1} removes approximately 180 kg ha^{-1} of N and 263 kg ha^{-1} of K (Kunkel et al. 1973). Grain crops are not as effective at removing nutrients and are very poor for treating salt loading unless the stover is also removed.

Recent research from Minnesota indicates that repeated N-based applications of potato waste on coarse-textured soils with low P sorption capacity can accelerate P leaching to groundwater and increase the risk of surface water contamination (Zvomuya et al. 2005). Results from the same study also indicate that, on high P soils, even the application of wastewater low in P concentration can cause significant leaching of P. Wastewater management on agricultural land must therefore take into account soil test P levels and the P sorption capacity of the receiving soil in order to minimize the risk of P loss to sensitive aquatic systems. There is evidence from recent research that chemical or by-product amendment application (e.g., alum) can increase soil P sorption capacity and allow higher hydraulic loading rates of food-processing waste (Zvomuya et al. 2006b). This could allow continued application of PPW to supply crops with N and other nutrients while minimizing the risk of P loss to ground- and surface water.

Land application of PPW has been very successful when managed using the best available science and technology. It is necessary to have adequate crop land available for treatment of the wastewater produced. It may be necessary to pipe the effluent some distance to ensure an adequate land base for treatment. The use of a balanced approach, where applications are compared with removals, coupled with annual soil monitoring is necessary to ensure the effective treatment and use of potato process wastewater while protecting the quality of land and water resources.

THE USE OF POTATO BY-PRODUCTS AS RUMINANT FEED

Most potato by-product is low in dry matter (DM) content (Charmley et al. 2000). Consequently, livestock feeding operations have developed in close proximity to potato processing plants, resulting in localized specialized feeding practices that are intrinsically linked to the plants. For example, in Prince Edward Island, two large processing plants produce 400 000 Mg of PPW, and the industry as a whole generates 80 to 100 000 Mg of cull potatoes (L.J. Halliday, personal communication). A large proportion of this by-product is used in the final feeding phase (finishing) of approximately 30 000 head of cattle destined for slaughter annually (Statistics Canada 2005). Similar relationships between processing plants and feedlots are found across Canada. Limited amounts of PPW are also fed to dairy cows, although this class of livestock is less suitable since variation in consistency of supply and nutrient content can have more serious effects in dairy cows than beef cattle (M. P. Snowdon, personal communication). The feeding of PPW to swine is limited to the cooked product since protease inhibitors in raw potatoes affect protein digestion in this class of livestock (Van Lunen et al. 1989).

Typically, potato by-products are fed as a mixture of the various components, the proportions of which vary according to production practices employed in potato processing plants (Tables 1 and 2). It is also possible to store separate waste streams on-farm and improve nutrient balance through on-farm blending. By-product is shipped from the plant as it is produced, with minimal holding time. On-farm storage ranges from dumping on a concrete or asphalt slab to storage in a water-tight covered bunker. Runoff from potato waste should be contained and prevented from entering water courses since it has a high biological oxygen demand and can contribute to eutrophication of surface waters.

Storage and Preservation of Cull Potatoes

Cull potatoes are produced in the fall. While table potatoes can be stored under a controlled atmosphere, this is not economical for livestock feed. Frequently they are stored fresh without any attempt at conservation, but the storage period is relatively short, typically 1 to 3 mo (Nicholson 1974). To extend the storage life of culls several ensiling methods have been devised (Lewis 1999). Potatoes can simply be left whole and covered in a large pile (clamp). Since potatoes are low in water soluble carbohydrate (most energy is as starch), they do not ensile well. Further, if the potatoes are left whole, microbial activity is restricted to potato surfaces. Better preservation can be achieved by chopping potatoes before ensiling, however excessive runoff losses may occur (Nicholson et al. 1977). An additional problem with ensiling is the high levels of soil contamination usually associated with potatoes. Soil-borne microorganisms such as *Clostridia* have a detrimental effect on the succession of silage microbial development resulting in unstable silage of high pH (McDonald et al. 1991). The likelihood of ensiling success can be increased by mixing chopped potatoes with low moisture fibrous feeds (3:1 wet weight basis), such as straw or hay (Nicholson et al. 1977, 1982). This method serves to absorb moisture from chopped potatoes and increases the DM concentration of the mixture to between 30 and 35%. It also assists in consolidation of the mass and exclusion of oxygen (McDonald et al. 1991). In this way storage life can be extended for up to 9 mo (Nicholson et al. 1982). The roughage acts as an absorbent and assists in anaerobism in the silo. However, these roughages are often

Table 3. Nutrient composition of some potato processing by products (g kg^{-1} DM)

	Dry matter	Crude protein	Fat	Calcium	Phosphorus
Cull potatoes	160–240	70–110	20	0.4	1.8
French fry waste	300–400	50–100	80–300	0.1	2.5–3.0
Potato steam peel	120–80	100–200	–	1.0–2.0	1.7–2.2
Dried potato meal	900–930	80–115	45–85	1.0–2.0	1.5–2.5

Table 4. Effect of substituting barley or corn with potato processing waste on apparent digestibility (g kg^{-1}) of an 80% concentrate/20% silage finishing diet

	% potato waste in concentrate		
	0	50	100
Barley/potatoes	685*a*	756*b*	736*ab*
Corn/potatoes	702*a*	755*a*	736*a*

a, b values within rows with different letters are significantly different ($P < 0.05$).

of low nutritive value and will reduce the overall feeding value of the mixture, but body weight gains of 1 kg d^{-1} are achievable (Nicholson et al. 1982).

Practical Aspects

Low DM content of culls and PPW has major implications in terms of transportation and storage. For every 1 Mg of dry feed, 4 to 5 Mg of water are also transported and stored. Consequently, the use of such products is limited by the distance of the plant from the farm and storage capabilities on the farm. Separation of nutrients during storage can be a problem as can leaching of soluble ingredients into the surrounding environment (DiCostanzo et al. 1994).

Low DM concentration exacerbates handling and feeding problems; consequently PPW is seldom fed as a high proportion of the diet (Charmley et al. 2000). Reducing the proportion of PPW reduces problems of freezing and spoilage. It also minimizes the impact of nutrient content variability in the PPW. The feeding of whole potatoes, especially when frozen, represents a choking risk to cattle and specialized, low-set feeding troughs are recommended (Nicholson 1974). However, freezing will help preserve the product from deterioration and allow for longer storage before feeding.

Inconsistency of PPW often limits its use in livestock rations (DiCostanzo et al. 1994). It is essential to be able to deal with component fluctuations by blending ingredients from several sources. The components that vary most are water and fat. Both of these can have profound effects on achieving a balanced ration. If rations are mixed on a wet weight basis, failure to adjust for variation in moisture will influence the inclusion level on a DM basis. Fat is a major problem when formulating PPW into beef rations. The ruminant digestive system cannot tolerate added fat concentrations much in excess of 5% of DM (Palmquist and Jenkins 1980).

Nutritive Value

Potato processing waste is a generic description for a heterogeneous mixture of potato components that varies depending on the nature of the processing method (Tables 1 and 2). Most PPW is characterised by low DM content, the exception being potato meal (DM content > 850 g kg^{-1}) which is sold as a high value feedstuff. For other forms of PPW the DM concentration ranges from as low as 100 g kg^{-1} up to approximately 400 g kg^{-1} (Table 3). The low DM concentration is attributed to the low DM content of potatoes (typically 160–240 g kg^{-1} DM) plus the use of large amounts of water in washing and processing, some of which remains in the PPW stream. This is in spite of the fact that separation of liquid waste occurs in the plant. In practice, PPW used in animal feeding is typically a composite feed containing various proportions of several waste streams within the plant. This ensures that extremes in moisture and other feed components are minimized.

Potatoes and their processing wastes are primarily energy feeds (Charmley et al. 2000). Being composed principally of starch, they are a poor source of protein, minerals and fibre (Charmley et al. 2000). While potatoes are low in lipids, some PPW, notably french fries, can have high lipid concentrations as a result of adding fat during processing (Table 3).

The metabolizable energy value of PPW (which has not been adulterated with exogenous fat sources) and cull potatoes for ruminants is intermediate between that of barley and corn, being approximately 13 MJ kg^{-1} DM (Rooke et al. 1997). Research trials substituting barley for potato waste have generally shown modest increases in digestibility (Stanhope et al. 1980; Onwubuemelli et al. 1985). In digestibility studies by Duynisveld and Charmley (2003), substitution of barley or corn grain with PPW resulted in a statistically quadratic increase in apparent digestibility of 80% concentrate diets (Table 4). The mixed cereal/PPW concentrates were more digestible than any of the single concentrate diets. By extrapolation to 100% inclusion in the diet, apparent digestibility of PPW has been found to be approximately 780 g kg^{-1} (Duynisveld and Charmley 2003). However, since starch granules in potatoes are larger than those in barley and higher in the proportion of amylopectin,

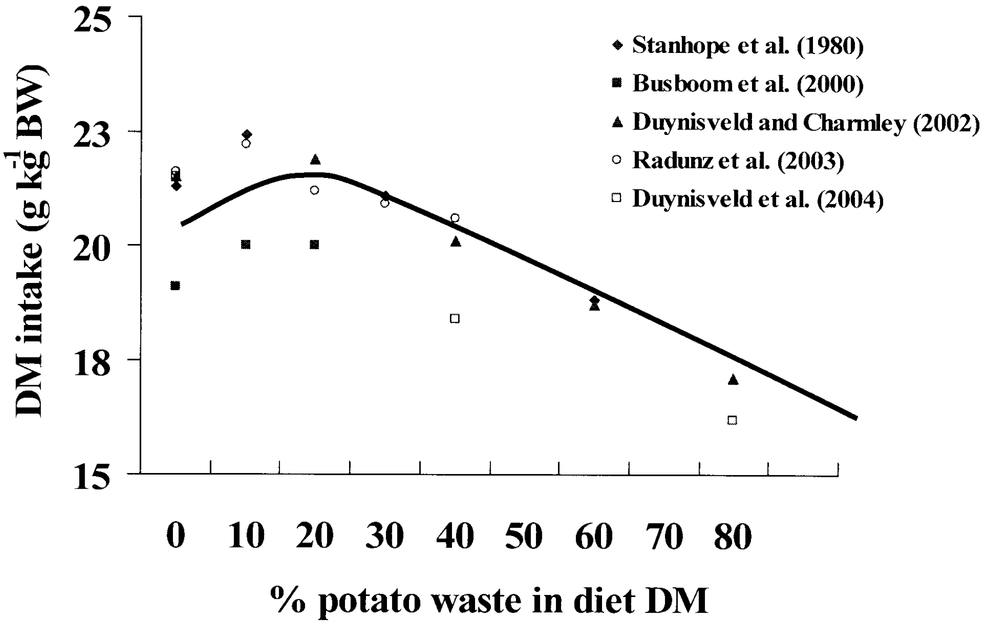

Fig. 1. The relationship between inclusion of potato processing waste (PPW) in the diet and DM intake by finishing cattle.

the starch in uncooked potato is more slowly degraded in the rumen than is barley starch (Cone et al. 1989). Thus, when Radunz et al. (2003) substituted corn for steam peel potato waste in graded diets ranging from 0 to 40% PPW, apparent OM digestibility was unaffected, but the amount digested in the rumen was reduced as the proportion of PPW increased. This relatively slow rate of rumen metabolism should result in a more balanced rumen pH and better utilization of nutrients by rumen microorganisms (Nagorka et al. 2004).

The inclusion of fat in potato processing can increase the fat concentration of PPW. For example, french fry waste can have a fat content over 200 g kg^{-1}. Ruminants cannot tolerate high concentrations of fat in the diet due to the sensitivity of the rumen biota to lipid. Typically, fat levels of ruminant diets should not exceed 30 to 50 g kg^{-1} DM (Palmquist and Jenkins 1980). Rooke et al. (1997) showed that increasing the proportion of french fries in the diet from 150 to 600 g kg^{-1} significantly reduced the extent of organic matter digestion in sheep. However, since french fries are usually mixed with low fat PPW, the fat in the resulting diet is diluted. The problem remains, however, of inconsistent fat content of PPW and an inability to estimate fat content of PPW on the farm. Wide fluctuations in fat content will result in digestive upsets in livestock, characterized by markedly reduced levels of feed intake.

Voluntary Intake

In any livestock production system, the amount of feed the animal eats is generally related to the level of animal production that can be achieved. From the few studies on feeding PPW (Stanhope et al. 1980; Rooke et al. 1997; Busboom et al. 2000; Duynisveld and Charmley 2002; Radunz et al. 2003; Duynisveld et al. 2004) it is apparent that increasing the level of PPW in the diet beyond about 20% results in a decline in DM intake (Fig. 1). Initially, cattle respond to the inclusion of PPW by exhibiting a small increase in voluntary intake. However additional increments in diet PPW content result in a decline in intake. Duynisveld and Charmley (2002) found a 20% decrease in voluntary intake when PPW was increased from 20 to 80% of the diet (Table 5). In a subsequent trial (Duynisveld et al. 2004), a decrease in intake was observed when potato waste replaced either corn or barley (Table 6). This characteristic response has been attributed to the low DM concentration of the diet (Busboom et al. 2000). However, research has shown that intake does not necessarily decline as the amount of moisture associated with the feed increases (Robinson et al. 1990). Further, Radunz et al. (2003) found no difference in ruminal liquid volume as the proportion of PPW increased from 0 to 40%. Using the same dataset as Duynisveld and Charmley (2002) and Duynisveld et al. (2004), Nagorka et al. (2004) concluded that adaptation to a potato-based diet lasted approximately 6 wk, and this contributed to the reduction in DM intake in the early feeding phase.

Animal Performance

Nelson et al. (2000) concluded that feeding low-fat PPW at up to 20% of the diet DM did not affect rates of BW gain or carcass weights. However, Radunz et al. (2003) found a negative quadratic response in rate of gain as PPW proportion in the diet increased up to 40%. At low levels of PPW (10 to 30%) gains were reduced, but they began to increase when PPW was fed at 40% of the diet. Duynisveld and Charmley (2002) obtained excellent BW gains from PPW at up to 80% of the diet, but observed a marked positive quadratic response to level of PPW inclusion. Thus BW gain

Table 5. Effects of substituting barley with potato processing waste in 80% concentrate beef finishing diets on production, carcass and meat characteristics

	Inclusion level of potato processing waste in the diet (%)					
	0	20	40	60	80	Probability^{z}
Production characteristics						
DM intake (g kg BW^{-1})	21.5	21.9	20.1	18.7	17.1	L
BW gain (kg d^{-1})	1.65	1.68	1.90	1.60	1.66	Q
BW gain (g kg^{-1} DM intake)	158	156	181	178	188	L
Carcass characteristics						
Lean meat (g kg^{-1})	590	591	589	596	589	NS
Backfat thickness (mm)	7.52	7.25	7.42	7.28	6.83	L
Meat characteristics						
Texture^{y}						
Juiciness	3.93	3.90	3.85	4.02	3.84	NS
Firmness	3.41	3.57	3.47	3.41	3.34	NS
Toughness	3.89	3.93	3.89	3.79	3.71	*L*
Beef colour^{y}	4.44	4.84	4.72	4.79	4.55	L
Beef flavour^{y}	3.92	4.18	4.10	4.18	4.05	L

^{z}L=linear ($P < 0.05$), *L* = linear ($P < 0.10$), Q = quadratic ($P < 0.05$), NS = not significant.
^{y}Assessed by a trained taste panel using an eight-point category scale.
BW = body weight

Table 6. Effects of substituting either barley or corn with potato processing waste in 80% concentrate beef finishing diets on production, carcass and meat characteristics

	Barley-based concentrate				Corn-based concentrate			
	% PPW in the concentrate				% PPW in the concentrate			
	0	40	80	Probability^{z}	0	40	80	Probability^{z}
Production characteristics								
DM intake (g kg BW^{-1})	22.4	19.2	16.3	*L*	20.5	17.7	16.3	L
BW gain (kg d^{-1})	1.49	1.32	1.44	Q	1.36	1.30	1.44	NS
BW gain (g kg^{-1} DM intake)	131	140	180	NS	136	151	180	L
Carcass characteristics								
Backfat thickness (mm)	9.51	10.4	9.7	NS	8.3	10.2	9.93	NS
Marbling score^{y}	5.94	6.03	5.29	*L*	5.83	5.66	5.26	NS
Lean meat (g kg^{-1})	589	519	568	Q	551	559	566	NS
Intermuscular fat (g kg^{-1})	109	140	116	Q	118	11	113	NS
Meat characteristics^{x}								
Flavour intensity of beef	9.25	9.30	9.41	NS	8.95	9.47	9.41	NS
Texture intensity of beef	9.62	9.75	9.50	NS	9.37	9.75	9.50	NS

^{z} L = linear ($P < 0.05$), *L* = linear ($P < 0.10$), Q = quadratic ($P < 0.05$), NS = not significant.
^{y}Assessed by a trained taste panel.
^{x}Assessed by a trained taste panel. Values are the sum of five attributes each measured on a three-point descriptive scale.

was maximized at 1.90 kg d^{-1} when PPW accounted for 40% of the diet (Table 5). Because gains did not decline with increasing levels of PPW, but were maintained with lower feed inputs, efficiency of feed utilization was actually higher (188 g kg^{-1} DM intake at 80% PPW *vs.* 158 g kg^{-1} DM intake at 0% PPW) as the concentration of potato waste in the diet increased. Subsequent research confirmed these findings (Table 6; Duynisveld et al. 2004).

Thus, it is clear that potato waste can replace conventional energy concentrates either partially or completely without negative effects on animal performance. In fact, the higher energy value of many potato waste products coupled with the slower rate of digestion in the rumen actually impart several nutritional advantages over either barley or corn. While cattle limit their intake of diets containing high levels of potato waste, this appears to be offset by higher digestible energy content. In practice, as mentioned earlier, PPW is seldom fed at high inclusion levels in the diet due to operational and ration balancing constraints.

Carcass and Meat Quality

Until recently, very little research had been conducted on the carcass and meat quality of cattle finished on diets based on potato or potato waste. Nicholson (1985) reported on a trial comparing barley- or potato-finished beef heifers, which showed no effects on cooking rate, weight loss upon cooking or drip loss of beef. Nevertheless, anecdotal opinion suggested that carcass and meat quality were inferior from cattle finished on potato-based diets compared with conventional barley-based diets. Charmley (1998) and Charmley et al. (1999) disproved these beliefs when beef roasts from commercial feedlots were assessed for eating qualities. This survey found that the nutritional management in the feedlot (potato-based, barley-based, silage/grain-based) had no effect on meat quality (grade and colour) and sensory characteristics (tenderness, flavour, juiciness, aroma). However, fat colour was lighter in potato-fed cattle than barley-fed cattle. In that study, cattle were taken from six feedlots representing approximately 30% of cattle slaughtered in the single regional packing plant. Thus, there was a wide range in management practices within the treatment groups. However, Busboom et al. (2000) obtained similar results under controlled experimental conditions. Increasing PPW to 20% of the diet had no adverse effects on tenderness, palatability and flavour. In fact, there were small advantages in terms of flavour when potato inclusion was increased. Radunz et al. (2003) achieved very similar results when PPW was fed at up to 40% of the diet. Again, it was apparent that meat eating quality was superior at higher levels of PPW inclusion.

Subsequent research has confirmed these findings (Duynisveld and Charmley 2002; Duynisveld et al. 2004). Polynomial regression analysis was used to test for linear or quadratic responses to level of PPW inclusion. In the first of two studies, beef steers were fed diets containing 80% energy concentrate. The proportions of barley and PPW were adjusted to give five treatments where the proportion of PPW was progressively increased from 0 to 80% of the diet. As PPW inclusion increased, lean meat yield was unaffected, but backfat thickness declined (Table 5). There were small positive effects on beef colour and flavour. Beef texture was unaffected, except that as PPW increased in the diet, toughness declined (Table 5). In the second study (Duynisveld et al. 2004), cattle were fed diets containing either 80% PPW, 80% corn, 80% barley or equal mixtures of PPW and corn or PPW and barley. Flavour profiles were assessed using a trained taste panel. There were no significant treatment effects on either flavour or texture attributes (Table 6). However, as in other trials, beef from cattle fed PPW ranked highest for all flavour scores. Thus, data ranging from a subjective survey to controlled experimentation all suggest that high levels PPW in ruminant diets do not adversely affect acceptability of meat.

CONCLUSIONS

Potato by-products are produced in large quantities across North America, typically in localized areas of production. In these areas, disposal of potato waste in landfills or through municipal treatment plants is limited. For disposal of PPW, land application has been the method of choice for many potato processors with access to appropriate land because of the fertilizer nutrient value (particularly N and P) of the wastewater and the deterrent costs associated with disposal through POTWs. While providing water to meet crop consumptive use, thereby reducing reliance on limited fresh water resources, land application of nutrient-rich wastewater can be used as an important supplement or even substitute for commercial fertilizers. Hydraulic and nutrient loadings, however, must match crop water use and nutrient requirements in order to avoid nutrient build-up in the soil and subsequent pollution of ground- and surface water.

Disposal of solid waste in landfills or on agricultural land is also limited in many areas where potato processing facilities are located. However, these solid by-products are of very high nutritional value as an energy source for ruminants. Beef feedlots have developed in these areas and are an effective means of transforming an environmental problem into an inexpensive feed resource. Research has conclusively demonstrated that very high levels of potato by product can be fed to beef cattle without detrimental effect on performance, carcass quality or meat acceptability.

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