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SYMBIOMA

Technology Innovations and Business Models for Valorisation of Industrial Waste Biomass in Sparsely Located Enterprises

Side streams from potato industries - quality and quantity

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Contents

SUMMARY

Potato production is the main staple crop in the NPA region, however potato waste utilization causes great concern in the food industry. In the potato production and processing industry the amount of waste fluctuates between years, mainly due to climatic conditions in the production, and can amount to between 20 % to 50 % of total yield yearly. The utilization of by-products and waste streams from potato production, varies between countries in the NPA region, where Norway is the only country having an established centralized system, where waste potatoes are collected and used for starch and alcohol production. Common for all four countries is that they see further opportunities for utilizing side streams for increased value and sustainability.

There are three main categories of sidestreams from potatoes:

- Dry unprocessed potatoes: potatoes which are left in the field, unsold potatoes due to quality problems or lack of marked and outsorted potatoes, excluding rotten potatoes.
- Disintegrated potatoes/processing waste: wet peel and grey water, waste from peeled, cut or sliced potatoes, potato juice and potato pulp.
- Source of low/no value: outsorted soil and rotten potatoes.

The various categories have different chemical composition, different current use in the region as well as differing potential for further utilization. The report discusses these differences. In particular, there are potentials for improved utilization of potato peels, pulp, and juice. New possibilities include as potato fibers, in biopolymer films, as a feed ingredient and in biogas production. In addition, there are great potentials for further biorefining/extraction of chemical components from the waste. This includes components with medical potential, as a source of several bioactive compounds, with potential for usage in the food industry as well as a protein source.

There are however several challenges for increased utilization of potato waste. These includes logistical issues due to short shelf life of waste, long distances and small volumes, lack of collaboration between industries as well as available infrastructure within relevant distance. In addition, there are challenges due to soil potato diseases, lack of technology, economic issues as well as yearly variability of waste amounts. By solving these challenges there are however a huge potential for valorization of potato waste.

A conclusion is that discarded potatoes, potato peel and potato by-products are available in large amounts and are resources rich in nutrients which have a potential for further utilization. However, production of higher-value products depends on the development of complex processes with several efficient processing steps, equipment, and techniques. Valorization also depends on up-scaling of optimized techniques for the extraction, and attention should be given on low-cost extraction methods.

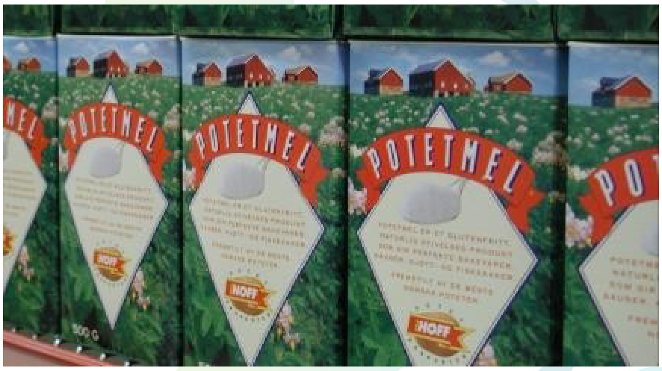

Figure 1: Potato flour from Hoff Industries, Norway (Photo: NIBIO)

Introduction

Potato is one of the most important agricultural crops for human consumption and is produced worldwide. In particular, the EU produced about 60.7 million tons of potatoes (FAO, 2020). Potato production is the main staple crop in the NPA region and Table 1 shows the total production area and volumes of potato in the four countries Finland, Sweden, Norway, and Ireland.

Table 1. Production areas and volumes of potatoes

Country	Production area (hectares)	Total yield (tons)
Finland	21 700	554 000
Sweden	16 000	300 000
Norway	11 572	332 000
Ireland	8 782	412 400

Food waste utilization causes great concern in the food industry, also in the NPA region. Handling of waste and sidestreams is a major limitation for expansion within the sector.

In the potato production and processing industry the amount of waste fluctuates between years, mainly due to climatic conditions in the production. Climatic conditions, such as droughts, too wet conditions in harvesting or early frost, causes variation in yearly total yield and quality. In addition, pest or disease may some years affect amounts of waste potatoes. Additional factors influencing waste amounts are agronomical practices and the potato varieties grown. Also type of processing (ex. peeling, washing, deep-freezing, heat treatment to potato food products causes various amounts of waste (Lindberg et al., 2016). Because of this, the amount of waste from potato production and processing varies between 20 % and 50 % of total yield from year to year. From theyield volumes in Table 1 this amounts to from 320.000 – 800.000 tons yearly in the four countries combined.

The utilization of by-products and waste streams from potato production, and with it the existingbusiness models, varies between countries (Reim et al., 2020).

For out-sorted potatoes Norway has established a centralized system, where potatoes are collected and used for starch and alcohol production. Finland has some well-established valorization routes, mainly for production of potato flakes (Ahokas et al., 2014)., while the system in Sweden is less organized. Ireland does not have any production of for instance starch, which could take care of out-graded potatoes.

The purpose of the Norwegian program is to ensure the efficient disposal of Norwegian-produced out-sorted potatoes. "Reutilization of out-sorted potatoes"[1] is under the governmental agency Norwegian Agriculture Agency. The contracted volume includes waste potatoes, but also potato pieces and starch water from potato processing. The coop owned HOFF Industries[22] organizes the use of these potatoes and produces starch as well as 20 000 tons for alcohol production (96%). The price is negotiated annually, and is reported as rather low, much due to high transportation costs for farmers with long distances to their processing plants. Which is especially the case for farmers in the NPA region. However, this program contributes to circular economy, utilizing the full potential of the potato yield.Common for all four countries is that they see further opportunities for utilizing side streams for increased value and sustainability, including the potential collaboration between farms and processing companies has in this regard.

Common challenges for all are the nature of the products, with high water contents and short shelf lives, as well as logistical challenges due to small production units and long distances. The situation is further complicated by potential potato diseases, especially PCN (potato cyst nematodes) which may spread with soil.

1 https://www.landbruksdirektoratet.no/nb/industri-og-handel/ordninger-for-industri-og-handel/avrensordning- for-poteter
2 https://www.hoff.no/198/om-oss

Sidestreams in the potato industry

There are three main categories of sidestreams from potatoes (origin given in parenthesis):

Dry, unprocessed potatoes

- Potatoes which are left in the field; small, and with minor damages (farmers)
- Unsold potatoes due to quality problems or lack of marked (farmers, shops)
- Outsorted potatoes, exl. rotten (grading by the farmer, processing or packing business)

Disintegrated potatoes/processing waste

- Wet peel and grey water (from peeled/cooked/fried potatoes)
- Waste from peeled, cut or sliced potatoes (from frying, peeling, cutting or other processing)
- Potato juice (starch production)
- Potato pulp (starch and alcohol production

Source of low/no value

- Outsorted soil (graded by the farmer, processing- or packing business)
- Rotten potatoes (graded by the farmer, processing or packing business

Rotten potatoes are usually identified during sorting/grading. The amount of rotten potatoes usually increase during storage.

These three categories of waste potatoes are discussed further below in coming sections.

Sidestreams from dry, unprocessed potatoes

These are potatoes which fail to meet the criteria of the preferred category (i.e. wrong size, shape, either on the peel or internally). They may be left in the field, remain unsold from the farm or retailer, or be outsorted on the way to the market, Storage can increase the amount of outsorted potatoes.

These potatoes have similar nutritional content and often the same shelf life as premium potatoesand potentially have a fairly high value as sidestream products.

A rough estimate of potato side streams of dry, unprocessed potatoes is 30.000 t in Ireland, 50.000 tons in Sweden, 45-50.000 tons in Norway (avrens) and 15.000 t in the NPA area of Finland.

Chemical composition

Potato tubers generally consist of 63–87% water, 9.1– 22.6% starch and other carbohydrates (mainly glucose, fructose and saccharose), 0.87–1.22% soluble fibres and 0.41–2.53% insoluble fibers(Ahokas et al., 2014). Minerals comprise around 1% of potato tuber weight. Potatoes contains small amounts of proteins (0.85–4.2%), fat (0.05–0.51%), trace elements and vitamins (6.5–34 mg 100 g-1 of vitamin C). In addition, potato contains antioxidants, organic acids, and anti-nutritional substanceslike the toxic thermotolerant glycoalkaloids.

Potato starch is located in starch granules composed of amylose and amylopectin (Storey, 2007). Starch concentration depends on species, cultivation conditions and season. The concentration of starch is highest in the peel and smallest in the middle of the potato. Potato fiber includes other carbohydrates than starch, i.e., cellulose, hemicellulose, pectic substances and pentosan. Those are present in tuber cell walls and intracellular structures, and they comprise approximately 2.3% w/w of potato (Storey, 2007). Main polysaccharides in fibers are cellulose (10–12%), pectin (0.7–1.5%) and hemicellulose (1%). Pectic substances are mainly protopectin (70%), soluble pectin (10%) and pectic acid (13.3%). Potato hemicellulose is composed of glucuronic acid, xylose, galacturonic acid and arabinose. Additionally, starch resistant to small intestine digestion is present (Storey, 2007).

Potato contains 6.9–46.3 g protein per kg of wet weight, the concentration being highest in the peel layer. Potato protein has a biological value of 90–100, which means excellent composition of amino acids for human nutrition. It contains nearly all the essential amino acids for humans, apart from methionine and cysteine (Storey, 2007).

<u>Present side stream products:</u>

- High value products: Some potatoes which are too small or have poor or damaged skin, butwhich satisfies the criteria for human consumption, may be sold for further grading or processing (i.e. peeling, dicing or as small potatoes) before reaching the retail chains.
- Flakes (most discarded potatoes in Finland)
- Production of potato granules, starch, glucose, and alcohol (most of these potatoes in Norway,which goes into the program "Reutilization of out-sorted potatoes")
- Biogas production (main use in Sweden)
- Animal feed
- Soil improvement (potatoes left on the field/farm in all countries)

Out-sorted potatoes not suitable for the intended product often holds sufficient quality for alternative products and gains the highest value by such use. One example is that potatoes with skinblemishes can be used for peeling and oversized tubers be used for dicing. A wide range of qualities can be used for flakes, and almost all qualities can be used for starch and alcohol production.

Potatoes for direct sales are less affected by strict quality requirements. Outsorted potatoes with a wider range of qualities can therefore be used for direct sales of fresh and stored potatoes. Visually impaired produce can also be channeled to community food banks and as stock feed sources.

Sidestreams from disintegrated potatoes/processing waste

Food waste utilization causes great concern in food industry in Europe and many scientific works and projects on this topic offer solutions and original approaches towards possible valorization of potato peels (reviewed by Sepelev and Galoburda, 2015, Gebrechristos and Chen, 2018, Abebaw, 2020, Kot el al., 2020). The majority of potato industry side streams are formed through peeling, cutting and packaging. Peeling of potatoes produces washing waters that include peel residues and potato fruit juice. In wet peeling 25–50% of the raw material ends up into residues. Its solid content is 10–15%, which also includes some earth and is therefore not usable as animal feed. Dry peeling produces 50–100% less side streams than wet peeling. Starch and alcohol production produces side streams including earthy water (produced during washing), peel mass (pure potato/potato pulp) and potato juice (Ahokas et al. 2014).

Table 2 Average composition of potato wastes (g/100 g) previously reported (reviewed by Torres and Dominguez 2020).

Content	Potato peels	Discarded potatoes	Starch processing wastewater
Crude fibre	13.0–25.9	6.8–7.5	0.2–1.3
Protein	13.9–17.9	1.5–2.5	15.1–19.2
Fat	2.6–8.5	0.3–0.9	0.2–0.5
Ash	8.5–7.9	0.8–0.9	0.2–2.3
Carbohydrates	39.9–56.2	9.9–25.2	1.5–21.1
Minerals[a]	0.8–98.6	0.3–3.4	0.1–1.8
Total phenolics[b]	11.5–79.2	4.2–96.6	6.2–13.1

[a]mg/100 g.
[b]mg acid gallic equivalent/100 g.

Wet peel and grey water

Much of the potato utilized in the processing industry are washed and peeled before furtherprocessing. Because of this, the potato peel is high in moisture content.

Potato peel waste is currently a zero-value or rather low value by-product, which occurs in big amounts after industrial potato processing and can range from 15 to 40% of initial product mass, depending various methods of peeling. Ireland estimates typically 6-10 % potato peel waste (PPW) from the peeling process (screening, grading, peeling) as well as other wastes (15%) from other trimming and cutting (slicing, blanching and disintegration) processes. Potato peels and grey watersin Finland estimates to 18 000 tons of per annum (Ahokas et al., 2014).

Potato peel possesses excellent nutritional characteristics. Potato peels are high in starch (8-28%) and contains about 1-4% protein. They may also be a good source of fiber and antioxidants which could be used as functional food ingredients. They contain a variety of valuable components, including phenols, unsaturated omega-3 fatty acids, including some rarely found in plants (Wu et al., 2012). Potato peels contain phenolic compounds in an amount ten times higher than that found in potato flesh (Singh et al., 2005).

They also have a high mineral content, being rich in iron (Wu et al., 2012). Peels also contain some cytotoxic glycoalkaloids such as α-solanine and α-chaconine. Suberin can be also obtained from peels (content up to 25% can be found in the periderm; Priedniece et al., 2017).

Present side stream products from wet peel:

- Feed for cattle (Finland, Norway water reduced)
- Compost/soil improvement (Finland, Norway, Sweden)Peel water is usually removed and disposed as grey water.

Side streams from starch and alcohol production

These productions may use potatoes contracted for starch but may also use sidestreams of out- sorted potatoes which fail to meet the criteria of the original use (direct human consumption or frying potatoes, due to for instance wrong size, shape, quality defects on the peel or internally, or too high sugar contents for frying). Starch (and alcohol) production results in two main by-products: potato pulp and potato juice.

Potato pulp

Potato pulp is the fiber fraction from the processing process. Pulp contains potato peel and cell wall residuals, with a dry matter content of around 14,5% (Hoff). Non-starch polysaccharide material (NSP) make up 60–65% of the solid. Some minerals are also included (K, P, Mg). The energy content of peel mass is around 13.6 MJ Kg-1 (Ahokas et al., 2014). Potato pulp is highly viscous and may be stored for some days due to natural lactic acid fermentation; however, it is advisable to use it fresh.

Around 3.000 tons (wet weight) of potato pulp is produced annually in Sweden, around 7.000 tons in Norway. Present use of potato pulp is mostly as fodder. However, some potato pulp is processed to potato fibers for use in bakeries and meat processing (Engdahl et al., 2011 in Torén et al., 2019).

Potato juice

Potato (fruit) juice is the protein fraction from production of starch, and contains all the constituents of potato tubers except starch and fiber. The composition of this material is subject to variation depending on the variety of potatoes, growing conditions, technology and starch extraction technology. As an example, potato juice can contain 3.6% proteins, 2.5% low molecular mass substances (sugars, salts and acids) and no more than 0.5% of starch (Kowalczewski et al., 2022). It also contains additional water from starch extraction, which makes it an aqueous dispersion containing approximately 5% dry matter. Potato juice is spoilt easy and difficult to handle. Its biological oxygen consumption is rather high and it may become a source of biogenic pollutants when released to the environment.

Around 100000 tons (wet weight) of potato juice are produced annually in Sweden. 4-7000 t is produced at one out of three locations in Norway.

Potato juice is at present used for:

- Fertilizer (Sweden, Norway)
- Biogas (Sweden, Norway, plans in Finland)
- Feed for cattle (Norway, mixed 1:1 with pulp)
- Thickening into protoamylase (juice concentration) (Norway)
- Separation of proteins for feed

An acid-thermal coagulation process may be used for extraction of proteins. These proteins show poor functional properties and contains glycalcaloids, which makes them unsuitable for human nutrition. Also, only 50% of the proteins undergoes coagulation (Baczkowicz and Tomasik, 1985). Inaddition, the remaining liquid fraction still have a fairly high chemical oxygen demand, up to 26 g O_2/L, and a low value for use as soil fertilization.

Sources of low or no value

Soils and rotten potatoes are generally considered as waste without any value.

Rotten potatoes are usually identified after harvest, during sorting/grading, but rot can also develop during storage. Rotten potatoes have very limited utilization. Some of this waste may end as compost, although there are several restrictions to utilize such compost due to a dangerous soil- borne potato disease (potato cyst nematodes).

Possibilities for the use of potato peels, pulp and juice

There is a potential for increased use of these potato side streams for food and feed. Products from potato processing may be used as antioxidant in food systems, as a base for fermentation reactions(if the starch is hydrolysed to low fermentable reducing sugars) or as a dietary fibre source. Potato peel waste (PPW) can serve as a basis for phenol extraction, ethanol, lactic acid and enzyme (α- amylase and β-mannanase) production through fermentation, and edible film production (Sepelev and Galoburda, 2015). Attention should be given on low-cost extraction method, and further investigation of innovative products within the fields of food preservatives, pharmaceutical ingredients, renewable energy and animal feed (Gebrechristos and Chen, 2018).

Potato fibers

A project with HOFF and RISE-PFI (2020-2023) searches for possibilities of producing a high value cellulose based fiber product from potato pulp. A promising application is as texturizer in gluten-free baking products. A project in Ireland also includes separation of functional fibres for use as texture ingredients in food (CyberColloids Ltd).

Dietary potato peel powder (5% and 10%) has been found by Singh et al. (2005) to have a positive influence on a series of health indicators in diabetic rats, like reduced oxidative stress and plasma glucose levels. The active compounds are probably the polyphenol and the dietary fiber fractions. Potato peel powder may be used directly as a partial flour replacement in dough, without causing significant changes in sensory properties if not exceeding 10% of the flour weight.

Biopolymer films

Potato peel mass, with its presence of starch (46%), pectin, and cellulose, has a potential for production of biopolymer films (Rommi et al., 2016). Such films may be produced from potato peel mass and glycerol. High-pressure homogenization (HPH) and HPH combined with heat treatment have been investigated as pretreatment technologies before film casting. HPH-treated potato peel mass yielded biopolymer films with similar barrier and mechanical properties as films prepared from pure potato starch, including complete impermeability to grease. Additional heat treatment of the peel mass enhanced starch gelatinization, resulting in improved barrier properties and smoother surface topography of the films. Films with similar appearance and quality were also obtained from starch-free potato peel mass, indicating that potato fiber rich in pectin and cellulose is likewise a suitable material for biopolymer film preparation after HPH treatment. The film is found to have excellent grease barrier properties, and to be highly resistant towards oxygen, but has a low resistance towards water and water vapour. Possible applications of such films are packaging of dry foods and films intended for mulching.

Feed ingredient

Several of the side-streams from potatoes are already used as animal feed. Another use of out- sorted potatoes was tested in an experiment in the project CYCLE, with ensiling of out-sorted potatoes for feed (Adler, 2017). Ensiling increases shelf-life and may add additional value to the feed. 4 tons of potatoes were cut by a traditional beet chopper, mixed with 1-13% beet pulp to suck up effluents, and with 3-10% grass silage to support ensilaging. The mix was compacted to a round bale of around 1400 kg and wrapped by an Orkel compactor MP2000. Challenges in the pilot was cutting of the potatoes and making the potatoes stick together long enough to wrap the bale completely. Adding vegetables and probiotic bacteria to the potatoes may increase the palatability and the value of the ensilaged feed product. After storage for 12 weeks, the bale with most additives had no effluents and a stable DM content of 29%. Both silages had a fresh, acidic odor at both samplings and pH values of 4.4-4.9.

Biogas

The high volume of potato peel waste produced globally renders it a suitable waste product for the anaerobic production of methane (Redcorn et al., 2018). Biogas (methane and hydrogen) may be produced from both potato peel and potato juice. Production of lactic acid may also be combined with methane production for value-added processing of potato waste. Biogas production via potato- waste digestion can be improved by the selection of the inoculum used in the digester. Both hydrogen-producing and methanogenic organisms may be selected to perform to improve production. Another improvement of methane production from potato peels may come from co- digestion with cow manure.

Biorefining/extraction of components

The interest in recovery of bioactive molecules from potato peel has resulted in a number of publications over the last years (i.e. Priedniece et al., 2017, Pathak et al., 2018, Gebrechristos and Chen, 2018, Hussain et al., 2020, Torres et al., 2020, Kowalzcewski et al., 2022). Emergence of alternative uses for potato side streams and development of technology for its processing is forced, among others, for environmental reasons.

Potato juice is in literature reported to be of high nutritional and biological value, and may facilitate the treatment of certain gastrointestinal tract diseases. The medical potential includes antimicrobial, antioxidant, anti-inflammatory, anticancer, antiobesity, antidiabetic, antihyperlipidemic, and antihypertensive activities of various constituents of the juice. Some of the compounds responsible for these activities have been identified (Kowalczewski et al., 2022).

Potato peel is also considered an interesting source of several bioactive compounds, among which are phenolic compounds, glycoalkaloids, polysaccharides, proteins, and vitamins. Such high value- added novel products may be used as antioxidants, nutraceutical and pharmaceutical formulations and cosmetic ingredients.

Potato proteins have a favourable amino acid composition and is allergen-free. They have a major potential for usage in the food industry, including the formulation of infant formula, and inclusion as a bioactive food (Hussain et al., 2020).

Potato proteins may be segmented into potato protein concentrates and potato protein isolates, of which concentrates are widely used in the feed and isolates increases within the food industry. The dominant producers in 2018 were Avebe (Netherland) Agrana (Austria) Tereos (France) Omega (US). Hussain et al. (2020) reviews different methods and principles used to isolate and purify the protein from potato juice. The most promising high yielding technique for feed appears to be precipitation, but if high quality and a white product is required then adsorptive membrane might be an optimal choice. Alternative methods used to keep the functional properties intact are expand bed absorption (EBA) and ion-exchange chromatography (IEX). Various methods may be applied to enhance the bioactive and functional properties of potato proteins, but most of these techniques are chemical- based. There is still a need for development of methods to produce high yield and high-quality products, particularly of more “green” technologies (Hussain et al., 2020).

Phenolic compounds present in potato wastes exhibited interesting healthy properties acting as antioxidant, antimicrobial or antitumoural agents, among others (Torres et al., 2020).

Phenolic compounds are mostly found around the peel, where around 50% of the phenolics are found (Rodriguez-Martinez et al., 2021) Phenolic compounds can be found in free, soluble (esterified), or insoluble bound form. Although most studies only focus on the free phenolic compounds, the great contribution of the esterified and bound phenols to the total phenolic compounds heightens their importance.

Potato side streams may be considered a source for extraction of a series of bioactive compounds. Among these are lactic acid, an important biomolecule applied in food, pharmaceutical and chemical areas, mainly to produce biodegradable polymers. Lactic acid can be produced from potato peel by an efficient fermentative process (de Oliveira et al.,2021).. Even glycoalkaloids, once considered only harmful, have proven to be useful for certain purposes (Kowalczewski et al., 2020). There are however still challenges to find effective downstream processes to obtain products with high chemical purity. Further research and development of economically feasible technologies are needed for full use of these valuable potato side streams.

General considerations

Discarded potatoes, potato peel and potato by-products are available in large amounts and are resources rich in nutrients which have a potential for further utilization. However, production of higher-value products depends on the development of complex processes with several efficient processing steps, equipment and techniques. Technologies for the reduction of the water content, such as membrane techniques or spray drying, are already available. However, due to the drawbacks of the conventional extraction methods, other novel alternatives for the isolation of bioactive compounds from potato skins are relevant. Among these techniques are: Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), Pressurized Liquid Extraction (PLE), Supercritical Fluid Extraction (SFE), and Supercritical CO2 Extraction (SSCO2). (Rodríguez-Martínez, 2021). Valorisation also depends on up-scaling of optimized techniques for the extraction.

Challenges:

- Logistical issues:
  - High water content, short shelf life of waste and byproducts
  - Long distances, small volumes (cost-efficiency)
  - Lack of collaboration between companies/districts/industries
  - Available processing plants within relevant distance
  - Right location for the site of valorization
- Restrictions due to potato diseases which may spread with soil (potato cyst nematodes, PCN)
- Need for additional technology (i.e. solid-liquid and pressurized liquid extraction techniques for the extraction of antioxidants)
- New products may create new side streams and waste problems
- Lack of economic incentives to change the use of by-products/waste
- Lack of motivation and the needed collaboration/organisation (within and between businesses) to make changes
- A variable source of raw materials within a year and between years. Different raw materials and processes also creates an inhomogeneous raw material
- A need for further research and the development of economically feasible techniques

Possibilities

- Collaboration with other producers of biological side-streams, within or between products, to increase the volume, i.e. for compost and bioenergy, but also for processing to food, feed or chemical compounds
- Improved processes for soil treatment/composting to overcome restrictions due to potato disease.
- Development of new processes and extraction of fractions for human consumption.
- Increased use for energy and biogas
- Feed for fish

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