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Resource assessment for potato biorefinery: Side stream potential in Northern Ostrobothnia

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Abstract. Potato industry side-streams consist of a significant amount of the original biomass. However, tightened demands of EU legislation together with the costs of side stream processing have forced potato industry towards more efficient use of the raw material. For this purpose, we have examined the possibility to recover main fractions from potato side streams, such as proteins, fibers and starch, and utilize them in a manner of biorefinery concept. The aim of the present research was to evaluate the potential for a potato biorefinery based on biomasses available at area of Northern Ostrobothnia, Finland. Study shows, that there is enough side-streams available to build a concept, which produces more value added products, like fibers and proteins. In this report, the main conclusions of the research are presented together with state-of-art on potato waste water processing technologies and current applications of their products.

Key words: side streams, potato, biorefinery, starch, fiber, protein, resource assessment.

INTRODUCTION

Potato production can be conducted in a variety of different conditions, which makes it a commonly cultivated crop across the world, also grown in all EU countries. Global annual production of potato is over 350 million tons from which EU countries produce nearly 55 million tons (FAO, statistics from 2012). Finnish annual production is approximately 500,000 t corresponding to harvested area of 20,700 ha.

The geographical scope of the table potato market is rather wide; competition between production areas is enabled due to tolerance of potatoes to carriage and thus low transportation costs. The rising demand for potato products in Central and Eastern Europe, in Asia and South America also offers new business opportunity for European potato producers. Potatoes used for processing have lower unit value, which leads to increased transportation costs compared to table potatoes. Thus the processing plants are located close to the cultivation areas.

The main center of production for Finnish potatoes is in Ostrobothnia, where the conditions are most suitable for the purpose. The present research focuses on area of

Northern Ostrobothnia, which extends across Finland from the Gulf of Bothnia coast to the Russian border and has an area of 37,000 km² and population of about 380,000 people (7.2% of the Finnish population). The harvest area of potato in the region is approximately 3,800 ha accounting to 114.9 million tons (Tike, 2013). The majority of harvest is used as seed potato or as food (table potato or food industry). Starch potato is not cultivated in large extend.

Potato cultivation and processing creates significant amounts of side streams that are not included in the main products. These are especially produced during processing of potato, *i.e.* peeling, packaging and washing, while harvesting residues comprise smaller but still remarkable share of non-used biomass. The amount of produced side streams varies from process to process; in some peeling processes up to half of the biomass ends up to side stream (Peusa & Piilo, 2006). Further processing of side streams is costly and thus affects economy of industry. It is also notable that the biological burden of these side streams is relatively high. For instance, biological oxygen consumption of potato peel mass can be 10,000 mg L – 1 (Peusa & Piilo, 2006) while that of municipal waste is only approximately 200 mg L – 1 (Riekkinen, 2007). Additional pressure comes from EU directives regarding end-of waste criteria for biodegradable waste subject to biological treatment (compost/digestate) in accordance with Article 6 of Directive 2008/98/EC of the European Parliament and of the Waste Framework Directive (JRC 2014). Thus, it is obvious that the valorization of potato industry side streams would be beneficial for both environment and industry.

Data on produced side streams in the research area were collected by interviewing of industry, supermarkets and potato farmers. Based on the survey, preliminary feasibility evaluation was prepared for potato biorefinery concept around main compounds in the side streams. By definition biorefining means sustainable processing of biomass into spectrum of marketable products and energy. The basis of this research was the assumption that biorefinery is the most feasible manner for optimal use of the produced side streams. The preliminary biorefinery concept was thus build based on the known composition of potato, the composition of processing side streams and the estimation of resource potential and location. In our further research we intend to develop necessary separation and purification processes for these compounds, and to integrate the developed processes as potato biorefinery concept.

MATERIALS AND METHODS

An assessment of potato industry side streams in Northern Ostrobothnia was conducted by direct industry survey. The survey was conducted during January–February 2012. The target group included 28 packing plants (seed and food potatoes), 7 potato processing plants (peeling plants, refining plants), and 11 large retail stores (supermarkets). The target companies were asked to describe the amount of produced side streams from potato production, processing and distribution, and the current use of these streams. The companies were also asked the current costs of processing the side streams and to evaluate, which price they would sell side stream potatoes. In total the survey included 15 questions.

Resource estimates were made of the quantities of materials produced and the potential for their use in biorefinery. Quantities of materials were estimated by summing the answers from industry survey. Based on known compositions of potato industry side streams, the initial biorefinery plan included separation and upgrading of starch, fibers, proteins and solid residues.

The main compound in potato is water, forming approximately 63–87% w/w (Storey, 2007, Burlingame et al., 2009). The other main compounds are starch (9.1– 22.6%) and other carbohydrates (mainly glucose, fructose and saccharose); and fibers, from which 0.87–1.22% are soluble and 0.41–2.53% insoluble. Potato bulb 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 toxic thermo tolerant glycoalkaloids 0.071–175 mg 100 g^{-1} (Burlingame et al., 2009).

Potato starch is located in starch granules composed of amylose and amylopectin (Storey 2007). Starch concentration depends on species, cultivation conditions and season; in spring potato it is 10% and in starch potato 21% (Kangas et al., 2007). The concentration of starch is highest in peels and smallest in the middle of potato in which it can be even totally absent (Karlsson & Eliasson, 2003; Virtanen, et al., 2005). Native potato starch is most suitable as filler and 'binding agent' and thus its properties have been changed to allow wider spectrum of applications, first with chemical means (Kraak, 1993) and later also biologically (Jobling, 2004). Modified starches are used e.g. in building and textile industries (Lyckeby, 2012). Starch production creates potato fruit juice (PFJ) and potato pulp as side streams, both of which contain proteins and fibers. These side streams could be utilized better which would eventually also improve the economy of industry.

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 (Kadam et al., 1991). Additionally starch resistant to small intestine digestion is present.

Potato contains 6.9–46.3 g protein per kg of wet weight, the concentration being highest in peel layer (Karlsson & Eliasson, 2003). The quality of potato protein depends on amino acid composition. The quality is measured using biological value, which describes the proportion of nitrogen in protein available for human consumption. If all of the nitrogen can be utilized in human body the biological value is 100, which is the reference value from egg white. Potato protein has biological value of 90–100 which means excellent composition of amino acids for human nutrition. It contains nearly all essential amino acids for human with only exceptions of methionine and cysteine (Storey, 2007). In addition, potato waste may include also high-valued protein fractions that could be utilized commercially (Schieber & Saldaña, 2009).

Minerals comprise 1.1% of potato tuber weight (Storey, 2007). According to research by MTT (Ahokas et al., 2012) dry matter mean value is 22.3%. The average concentrations of phosphorus, potassium, calcium, sulfur, sodium, magnesium, copper, mangane, zinc, iron and boron of five different cultivars has been studied in field tests during 2005–2011 (Table 1).

Table 1. Minerals in potato tubers (Ahokas et al., 2012)

Element $g\ kg^{-1}$	P	K	Ca	S	Na	Mg	Cu	Mn	Zn	Fe	B
	1.9	21.7	0.3	1.2	1.5	0.0	0.0046	0.0076	0.0113	0.0339	0.0065

The majority of potato industry side streams are formed during peeling, cutting and packaging. Peeling of potatoes produces washing waters that include peel residues and PFJ. In wet peeling 25–50% of the raw material ends up into residues. Its solid content is 10–15%, which includes also some earth. Therefore, it is not usable as animal feed. Dry peeling produces 50–100% less side streams than wet peeling. The produced side streams include earthy water (produced during washing), peel mass (pure potato), starch and PFJ. Peel mass (potato pulp) resulting from the industrial starch processing is highly viscous and contains 16–17% by weight of dry matter of which 30–35% starch and 60–65% non-starch polysaccharide material (NSP) (Mayer et al., 2008). Additionally minerals are included (K : 20 $g\ kg^{-1}$, C : < 0.8 $g\ kg^{-1}$, P : 1.4 $g\ kg^{-1}$, Mg : 0.85 $g\ kg^{-1}$). Peel mass may also be stored for some days due to natural lactic acid fermentation; however, it is advisable to use it fresh (Peusa & Piilo, 2006). The energy content of peel mass is 13.6 $MJ\ Kg^{-1}$ (Peusa & Piilo, 2006).

Table 2. The yield estimate of value added products from potato residue feedstock.

Product	Yield $kg\ t^{-1}$	Available products in market
Recovered wastewater	2,000	Process Water,
Ethanol	33[1]	Several potable vodka brands
Potato protein	10[2]	Tubermine®, PRO GO™,
Potato protein isolate	0.6[3]	Slendestra™, SUPRX™, Gly-Sea-Max™, Solathin™
Potato fiber	38[4]	Vitacel™, PENFibe®RO, Pofiber (Semper), Potex

[1]Izmirlioglu & Demirci (2012) (33g L-1 ethanol from waste potato mash); [2]Approximate value based on Karup Kartoffelmelfabrik (2007); [3]US Patent 6414124 2002 (900 mg kg^{-1} potato); [4]Mayer et al. (2012) (24% by weight of the pulp dry matter)

The amount of produced PFJ is approximately 70% the whole peel mass. It is easily spoiling and difficult to handle and its biological oxygen consumption is rather high. PFJ contains 23.5% solids which is formed by starch (17.4%), proteins (2.5%), fibers (1.8%), soluble carbohydrates (0.5%) and minerals (1%) (Bergthaller et al., 1999). Nutrients are present as follows: N : 0.33% (from which half is soluble), P : 0.045%, K : 0.47%, Mg : 0.03% and Ca : 0.002% (Riekkinen, 2007). PFJ may be utilized as fertilize in farming according to respective legislation (Peusa & Piilo, 2006).

Cutting processes produce classification and cutting residues. In addition, spoiled, under – or over dimensioned and incorrectly shaped potatoes are discarded to waste during packaging (Peusa & Piilo, 2006). The amount and solid content of side streams vary between processes.

The preliminary biorefinery concept was designed as a basis for the resource assessment and estimation of biorefining potential in the region. This concept is based on literature review on potato side streams, composition of potato and existing technologies for separation and purification of main components starch, fibers and proteins. To calculate material balance, certain yield values were chosen based on the literature review. These yield values are presented in Table 2.

RESULTS AND DISCUSSION

The response rate of industry survey was 72%, which was considered sufficient to assessment of resource potentials. The results of industry survey are summarized in Table 3.

Table 3. The results of industry survey. Standard error of the mean in parentheses

Product	Answers (n)	Treatment capasity T a^{-1}	Sorting waste t a^{-1}	Potato residue (in total) t a^{-1}
Seed potato packing	14	450–9,000 (1,513)	25–250 (44)	1,600
Food potato packing	8	1,500–10,000 (955)	250–1,000 (95)	3,700
Potato peeling	4	180–3,500 (706)	90–480 (80)	1,100
Markets	7		8–90 (10)	220

Packaging plants classify the potatoes in order to remove spoiled, under - or over dimensioned and incorrectly shaped potatoes. A minor part of harvest is usually left unsold e.g. due to excess supply. The annual processing volumes at seed potato packaging plants and food potato packaging plants were 450–9,000 t a^{-1} and 1,500–10,000 t a^{-1}, respectively (Table 3). Potato processing steps and produced side streams at a typical seed and/or food potato packaging plant are presented in Fig. 1.

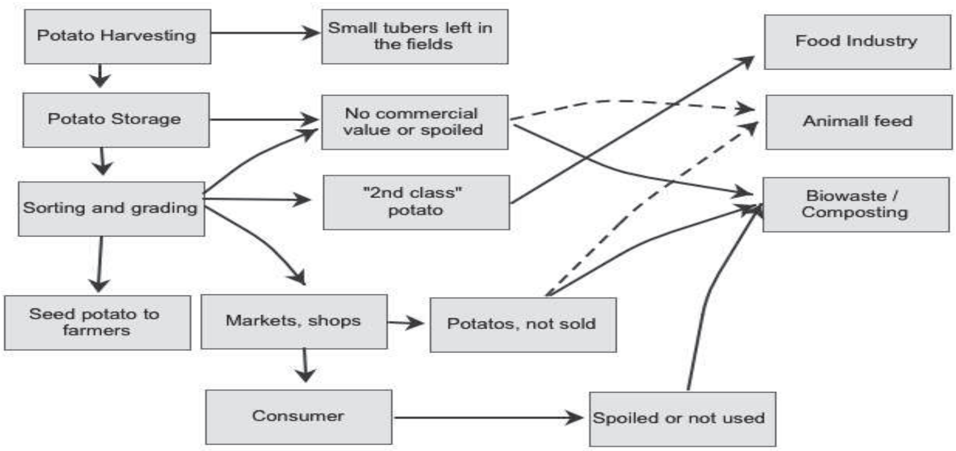

Figure 1. Process steps and produced side streams at a typical seed or food potato packaging plant. Solid line – primary use of side stream, dashed line – secondary use of side stream.

The amount of unsold potatoes at seed and food potato plants are 3–15% and 10–17% from total raw material, respectively. The difference is due to possibility of seed potato packaging plants to direct unsold potatoes to be used as food. In total, side streams from potato packaging plants count to approximately 5,000 t a^{-1}, from which approximately 85% is further utilized at food production (2^{nd} class potatoes). Thus, only 15% of packaging plant side streams, accounting to 1,100 t a^{-1}, can be included in the total side stream potential of the region. This residue is currently composted and used either as fertilizer or animal feed. However, companies are willing to sell their side streams if the income from it would be higher than current prices for 2^{nd} class potatoes, and the transportation of biomass would be arranged without extra cost. Based on our estimation, the price should be approximately 13 euro t^{-1} without transportation cost.

Approximately half of the interviewed packaging plants are able to wash the potatoes before packaging. Washing waters contain mostly earth and they are processed by sedimentation and sand filters. The recovery of biomass compounds from these waters can be considered unprofitable (Lehto et al., 2007).

Based on visual evaluation of potato farmers, approximately 5% of the harvest is left to fields. The majority of this residue is formed by under dimensioned potatoes. The exact amount of the residues is likely to depend on several factors, such as earth humidity and specifications of harvest equipment. The farmers recognized possibilities for improved harvest e.g. via minor equipment adjustments; however, this choice is not attractive unless the price for 2^{nd} class potatoes increases. In regional context the harvest residues may be up to 6,000 t a^{-1} accounting a significant amount of biomass.

The major potato processing plants in the region are chip production plant in Pyhäntä and multiproduct plant in Vihanti. In these processes 27–54% of the raw material ends up to side streams which accounts to 16,100 t a^{-1}. Vihanti plant share of this is 15,000 t a^{-1}, from which the majority is used in animal feed. This side stream is composed of classification and peeling residues of 1^{st} class potatoes, and peeling residues of 2^{nd} class potatoes that are used for potato flake production.

Other processing plants, mostly operating as peeling and cutting units, direct their peeling biomasses either as feed or composting. The estimated total side stream potential from peeling plants is 1,100 t a^{-1}. The process steps of potato processing plants are presented in Fig. 2.

Peeling plants that employ grinding method produce large amounts of starch containing water and PFJ. According to survey this side stream can be of similar size as the solid peeling residue. The surveyed companies used sedimentation, filtration and centrifugation for separation of solids. Centrifuges were generally considered effective but also too expensive for small companies.

Answers were received from 7 out of 11 surveyed retail stores. The annual amount of unsold potatoes, vegetables and fruits was 8–90 t a^{-1} in each store. The majority of this residue consisted of fruits and vegetables. Thus, the potential of potato side stream from the retail stores is rather low. Furthermore, retail stores suggested that the side streams should be removed in short sequences, several times a week, which together with small amounts of produced side streams would lead to relatively high logistic cost. Currently these residues are mostly composted which also generates costs to the companies. Small portion of the residues ends up as animal feed.

In terms of feedstock potential the most feasible location for the biorefinery would be in the proximity of Vihanti plant. The biorefinery would operate using side streams of potato flake production and peeling residues which results to minimal effects on material balances in plant itself. This would reduce the use of side streams for animal feed production. However, if bioethanol is produced in the biorefinery, also 2nd-class potatoes could be applied for this purpose.

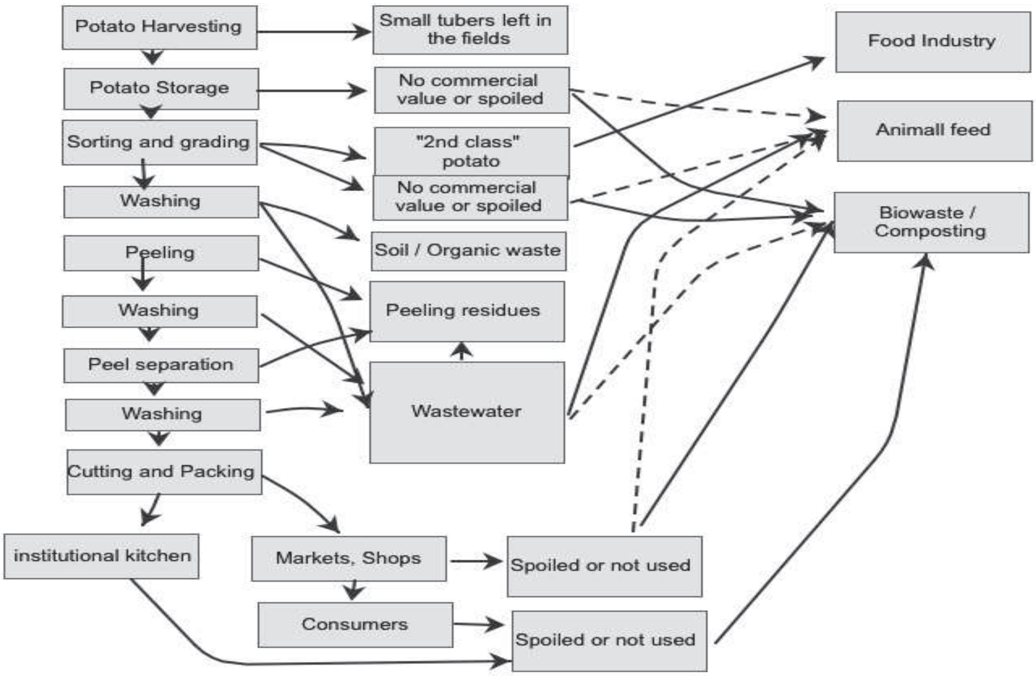

Figure 2. Process steps and produced side streams at potato processing plants. Solid line – primary use of side stream, dashed line – secondary use of side stream.

Based on rough estimations, the capacity of biorefinery could be approximately 20,000 t a^{-1} biomass feedstock for its operation. According to the present results 17,000 t a^{-1} could be acquired within the studied region with relatively small arrangements. The acquisition of retail store side streams could add to regional side stream potential if it could be feasibly arranged. The potential could be further increased if the use of harvest residues could be arranged in a feasible manner.

Considering maximal logistic cost of 10 euro t^{-1}, feasible range for feedstock transportation would be approximately 130 km (Paappanen et al., 2008). The respective zone of supply would include the whole region of Northern Ostrobothnia and areas of Central Ostrobothnia. It can be assumed that sufficient amount of feedstock is available within this area. However, it is notable that the availability of side streams depends on both annual harvest and potato demand, and therefore the annual feedstock demand of 20,000 t may not be available at all times.

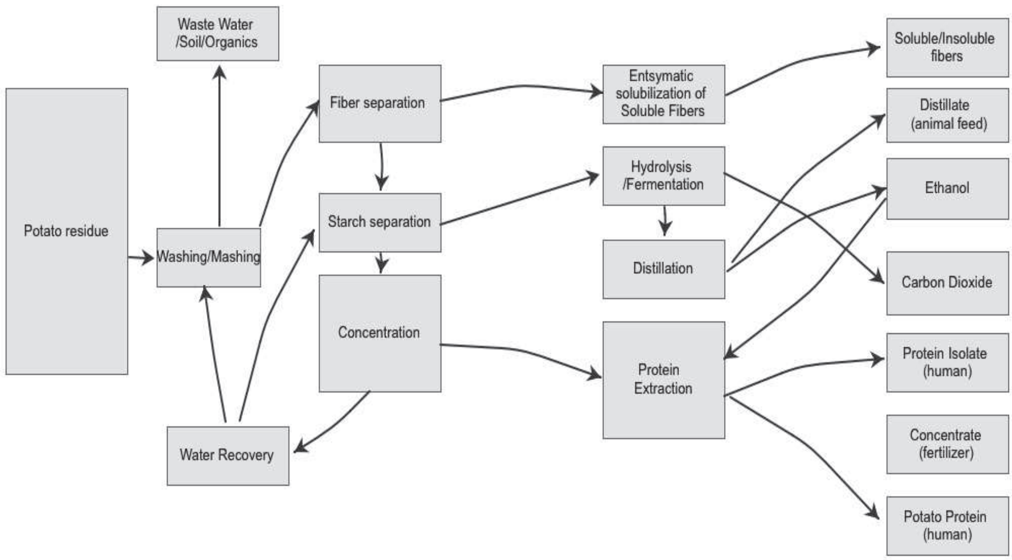

Figure 3. Estimation of material flow for potato biorefinery.

Material flow was estimated using the values from literature presented in Table 2. Assuming a feedstock of 20,000 t a^{-1} the potato biorefinery would produce 660 t a^{-1} ethanol, 760 t a^{-1} potato fiber, 200 t a^{-1} potato protein and 12 t a^{-1} protein isolates Also 40,000 tons of waste water can be recycled. Estimation of material flow is presented in Fig. 3.

CONCLUSION

1. The total potato side stream in the studied region would be about 17,200 t a^{-1}. The biggest side stream (15,000 t a^{-1}) comes from Vihanti potato product plant. At the present, main part (85%) of packing plants side stream is transported to Vihanti plant for potato flake production.
2. Only 15% of packing plants side stream (1,100 t) and the peels (1,100 t) can be added to Vihanti plant side stream, when estimating total side stream of the region.
3. Based on rough estimations biorefinery would require approximately 20,000 t a^{-1} biomass feedstock for its operation. According to the present results 17,000 t a^{-1} could be acquired within the studied region with relatively small arrangements.
4. The acquisition of retail store side streams could add to regional side stream potential if it could be feasibly arranged.
5. The potential could be further increased if the use of harvest residues could be arranged in a feasible manner.
6. In terms of biorefinery operations, significant role is played by the feedstock availability.
7. It is important to obtain low-cost but high yield chemical recovery process.
8. According to presented biorefinery concept, potato protein conversion, including ethanol recovery process and fiber production to high value products seems to be the most beneficial technical solution.

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