Potato Research (2023) 66:385–427
https://doi.org/10.1007/s11540-022-09576-7

On Processing Potato 3: Survey of Performances, Productivity and Losses in the Supply Chain

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Received: 11 April 2022 / Accepted: 16 July 2022 / Published online: 15 August 2022

Abstract

Potato has strong links between the actors as varieties bred by breeders, crop management of growers and site location of processors strongly influence the yield and quality of the finished products. Here, the actors (breeders, growers, processors, retailers and users) in the value chain are recognized, and their information and material flows identified. The influence of genotype, environment and crop management and the efficient use of resources during the production of raw material, tubers harvested for processing purposes, are delineated. It is shown that climate change affects performance and that consumers looking for quality and new products are hardly interested in the primary processes, nor are breeders and processors showing interest in consumer concerns. Crop performance is dependent on yield and quality (dry matter, sugars, tuber size and desired and undesired constituents). Factory performance relies on recovery, reuse of rejects and avoidance of wastes. Heatmaps drawn of classes of productivity and losses and their attributes reveal where gains are to be made on fields, farms and factories to improve efficiencies, reduce the impact on the environment, and opportunities for decarbonisation.

Keywords Biodiversity · Decarbonisation · Efficiency · Environment · Factory · Farm · Recovery · Wastes

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Introduction: Inception and Research Questions

Compared with the cereal staple foods, links between the breeder, seed grower, ware grower, processor and outlets are much stronger with processing potatoes. This is because the clonally multiplied crop has a special basic and certified seed programme and variety-specific characteristics play a central role in making starch, flour, French fries, and baked and chilled products. Information is conveyed from the consumer, through shops, processors, growers and breeders and its magnitude increases with each link passed. Material flows in the opposite direction, breeders' seed, basic seed, certified seed, raw material, finished product, packed according to own or shop's brand, pantry, pan or oven. To supply the market, raw material needs to be produced and processed with minimal losses. The following domains are distinguished: the supply chain, the performance of farms and factories, and losses at farms and in factories. Defining classes and their attributes in these domains and assessing the degree to which the attributes apply to the different classes is an innovative approach hitherto not found in scientific literature.

Where consumers are mainly interested in convenience, taste and environment-friendly production, shops add attractiveness and shelf life, processors add value to raw material, growers add yield through new techniques, and breeders add quality traits, resistance, tolerance and recovery-promoting traits. The information and material flows in the potato products supply chain need to be identified and their links are described as follows: preparation in kitchens, processing in factories and production of tubers on farms. Performance of production such as yield, dry matter, sugar concentration and other quality aspects depends on the variety planted, the prevailing environment and that as affected by climate change, where grown and the cultivation techniques employed resulting in use efficiencies of resources, among them land, water and energy. Performance of processing and recovery of dry matter and also of its constituents as a proportion of finished product of tubers grown depend on losses at harvest, handling, storage and processing. But to what degree?

The performance of the crop, at harvest and pre-harvest, its yield and quality, and the efficiencies to a large extent are a function of the variety and seed quality planted, the environment where the crop is grown and the management practices of the farmer (Survey 1, Haverkort et al. 2022a). Post-harvest performance, i.e., the recovery of finished product, is a function of on-farm handling, storage between harvest and delivery to the factory and the kind of operations in the processing plant from washing to packing (Survey 2, Haverkort et al. 2022b). To be able to judge the efficiency of field and factory production, an analysis of yield is needed: what are the classes of yield components (quality), what are their attributes, among them the effect of climate change, and how much do they vary in exerting an influence on quality?

Efficient use of resources not only depends on the quantity of tubers produced and products made but also on losses and wastes on farms, in factories, shops and kitchens. How efficiently are energy and water used in manufacturing? Which classes of losses exist in each link of the supply chain? How are they affected by the environment and management? The subject needs to be discussed in the light of sustainability issues: resource availability (fresh water), emissions (CO_2) and climate change (elevated CO_2, increase in temperature and erratic precipitation patterns). Avoidance of losses is the attribute of the classes of losses and there is a need to identify these losses and to which degree they apply to the classes.

In field production of tubers destined for processing, transport and processing too are associated with withdrawal of resources such as water and habitat for fauna and emissions of deleterious substances, carbon dioxide and nitrogenous compounds. Which operations on farms and in factories are associated with undesired and harmful withdrawal and emissions, to what degree and which measures keep them within bounds?

Not all tubers grown in the field are delivered to the factory and not all tubers received end up as high-value finished products. Losses (not-recovered tuber material) and wastes (unused inputs and resources) are incurred on farms and in processing plants. It has not been thoroughly assessed what these losses are and how they can be avoided with varying degrees of the chance of success.

Supply Chain Domain

Formulation of the Chain Domain

In a narrow sense, the potato sector or potato industry encompasses all activities carried out by potato breeders, seed potato growers and growers of tubers meant to be used as raw material and by processors buying and processing the tubers. Potato breeders exist in a wide variety. There are individual, single person breeding companies and larger ones that annually produce millions of seedlings as it takes some hundred thousand seedlings of two parent clones to create a variety. The company has shareholders or is owned by a farmers' cooperative (Van Loon 2019) and both types may have farmer breeders, farmers receiving a few thousand seeds or seedlings to assist in selecting a new variety. Occasionally, processing companies have their own breeding division such as the largest starch industry in the Netherlands and the largest potato chips maker in the USA. Seed potato production in developed markets in general takes place in three stages by one company but often involving three different firms: (1) the creation of in vitro plantlets and mini-tubers thereof, (2) production of basic seed in about three field stages, and (3) producing certified seed in another three to four field cycles. In developing markets, usually, the multinational breeding company, in order to assure a regular supply of the favourite variety, owns all steps. Local companies in such markets, especially when making chips, depend on what the growers have on offer or pay a higher price for lots meeting specifications. Growers of the raw material may have a small area of less than a hectare in developing markets or over a thousand in Idaho (USA). They sell their crop, generally on a contract base to the processing company. The processors' procurers (with agronomists in the team who carry out research and development for the company and also advise growers) are in close contact with the growers to assist them and monitor yield and quality for factory intelligence. In developing markets, processors also, initially, grow their crops on rented land. This corporate farming assures the regular supply but as soon as the grower base has been trained, growing own tubers is abandoned. Processors make the products for the outlets retail, institutions and food industry. In this section retail, cooks and consumers are included in the supply chain. Providers of equipment, materials and services for breeders, (seed) growers, and for outlets are not included in the chain as formulated here.

Condensation of the Chain Domain

The value chain of potato-based products is aimed at reinforcing current, and establishing new consumer-product combinations and at an efficient means of communication from consumers to sales and down-chain links, and among links (Kiil et al. 2019). It also serves as a rapid upstream of materials (Olsen and Aschan 2010), i.e., tubers and products (Table 1). The cook's desire is ease and time-saving and (s)he is not necessarily the person buying the products nor consuming the dishes prepared from them, in restaurants for instance. Upstream the cook communicates the quality of the dish with the eaters, its advantages and disadvantages with other cooks and communicates the preferences for future products with shops. Trade firms, shops and supermarkets are interested in rapidly overturning shelf space informing customers of products' advantages and producers of their requirements. Factories usually make several products such as frozen French fries, formed products and flakes or chips, so the specifications of the raw material vary, and there is a constant need to adapt varieties to changing conditions such as black listed chemicals, growers moving to more marginal lands and governments restricting irrigation water or biocide use. Buyers of tubers from growers, procurers, are the only actors that do not actually own any material, they go between, and convey specifications to growers. They work closely with the company's agronomists who act as consultants for the growers with the ultimate aim to assure that the raw material meets the specifications and inform procurement of the quantity and quality of the current crop in the field, at harvest or in the potato stores of growers and of the company's own store where applicable.

Aligning seed of new and current varieties among breeders, seed producers and growers of tubers to be processed is aimed at assuring the fulfilment of the processors' needs. Where information trickles down from the cook to the breeder, a stream of material goes the opposite direction: breeders deliver basic seed tubers to seed growers who provide growers with seed from which they grow the raw material. Products are handed over from producers to shops, customers and cooks ending up as ingredients for dishes for eaters.

With variety (ADHB 2021) being an important factor (besides environment and crop management) that determines the recovery of finished product from raw, a most intensive finetuning takes place between breeders and processors. This is especially the case when the processing company is interested in assuring the exclusive right to deploy a new variety, to be in control of it rather than sharing it with the competition.

These activities, aims and deliberations, iterative processes, are shown in Table 2. The first two rejection rounds of seedling clones include low yielding off-types

Table 1 Flows of information and material among classes of actors in the potato product value chain

Classes of actors	Desire	Flow of information upstream	Flow of information downstream	Flow of material upstream
Eater	Taste, origin	Share with friends	Tell the cook	Left over waste
Cook	Convenience, ease, safety, health	Performance for peers	Performance	From pantry to stove
Customer	Optimize price quality	Product preference	Consumption pattern	From shop to pantry
Trader	Rapid turn-over of shelf space	Product information Product range	Requirement of products	Product from factory to shelf
Processor	Optimized recovery	Availability of finished products	Need of tubers according to specifications	Deliver products to trade
Procurer	Continuous flow of raw to factory	Quantity and quality of lots of raw material	Quantity and specifications of raw	Raw material (tubers to be processed) from farm to factory
Agronomist	Assuring growers meet quantity and quality	Provide information on quantity and quality to be expected	Consulting growers on optimal management practices	Raw material (tubers to be processed) from farm to factory
Grower	Meeting specifications	Availability and management practices	Demand of seed tubers	
Seed producer	Meeting demand of growers	Seed quality characteristics	Wants new varieties better meeting specifications	Seed tubers
Breeder	Resistant, adapted, processing quality	Variety characteristics: resistances, tolerances	Interacting with knowledge institutions	Basic seed tubers

Table 2 Crucial steps in creating a processing variety

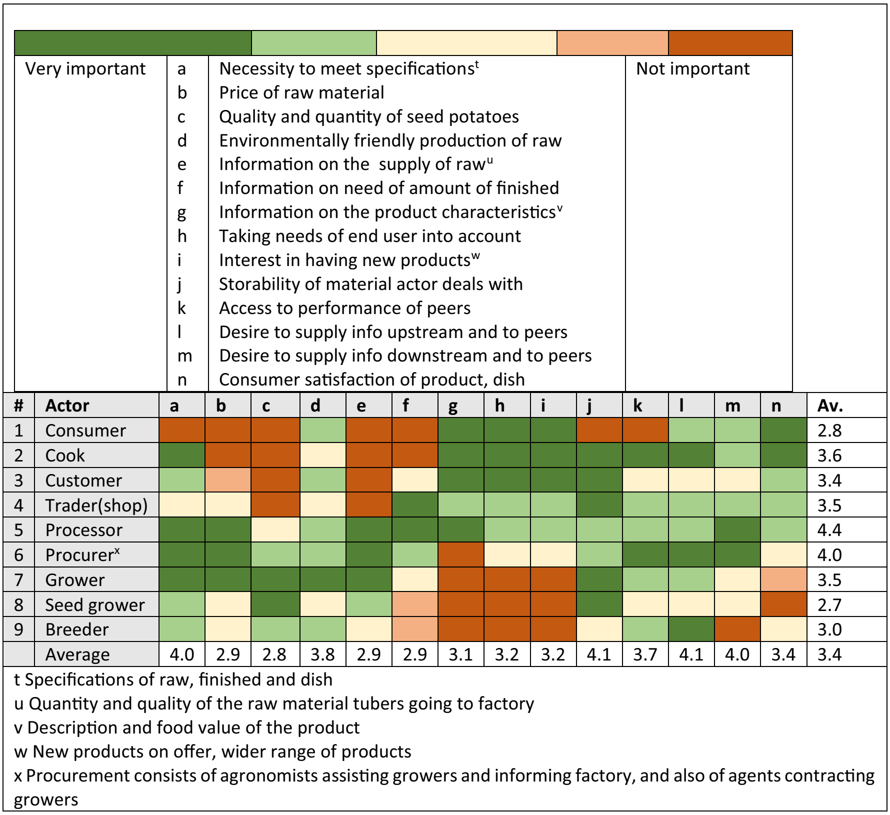
Activity	Aim	Rejection reasons for a manufacturing company
Selection and crossing of parents	Establishing processing potential	Parents lacking 1 of 3 (suitability, adaptability, resistance)
Selection of processable clones, lab approach	Detecting suitable dry matter, fry colour, shape	Not meeting all three criteria, besides yield, adaptation and tolerance
Bulking tubers of selected clones in the field	Obtention of sufficient tubers for factory runs	Factory trial runs show different data than lab/kitchen conditions: peeling, cutting (shear), blanching (discolouration) conditions differ, rejection follows disappointment
Factory runs with several tons of tubers	Assessing performance of advanced clones under factory conditions	
Bulking seed	Assuring enough seed to rapidly launch a new variety	Seed and crop health and tolerance of insects and drought play a role in the assessment
Variety naming and licencing	Protecting intellectual property	If exclusive rights cannot be guaranteed (non UPOV)

and as of the third year kitchen/lab-type assessments of dry matter concentration (under water weight), fry colour (reflecting concentrations of reducing sugars) and shape (length:width ratio). Breeding and selection result in factory trial runs after some 6 years of selection. Seed tubers of an outstanding clone that met the criteria in previous seasons are rapidly bulked to provide the factory with several tons of raw material to be subjected to factory processes. Recovery whereof is compared to that of currently employed varieties. When advantageous from the processing (high recovery) and production (efficient cropping) points of view, a company assures exclusive rights provided a fixed annual amount, which is mutually guaranteed upon.

Quantification of the Chain Domain

Nine actors of the ten (agronomy and procurement are one team) of Table 1 are given fourteen wishes and needs (attributes) listed in Table 3, each of them to a greater or lesser degree important for a particular actor. The heatmap shows that supplying information up- and downstream (and to peers where competition is not at stake) is important for all actors, so is meeting the specifications. Breeders are at the bottom of the

Table 3 Heatmap of the 9 classes of actors and 14 attributes the degree they are important for an actor



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Very important			Not important
	a	Necessity to meet specifications[t]	
	b	Price of raw material	
	c	Quality and quantity of seed potatoes	
	d	Environmentally friendly production of raw	
	e	Information on the supply of raw[u]	
	f	Information on need of amount of finished	
	g	Information on the product characteristics[v]	
	h	Taking needs of end user into account	
	i	Interest in having new products[w]	
	j	Storability of material actor deals with	
	k	Access to performance of peers	
	l	Desire to supply info upstream and to peers	
	m	Desire to supply info downstream and to peers	
	n	Consumer satisfaction of product, dish	

#	Actor	a	b	c	d	e	f	g	h	i	j	k	l	m	n	Av.
1	Consumer	🟫	🟫	🟫	🟢	🟫	🟫	🟩	🟩	🟩	🟫	🟫	🟢	🟢	🟩	2.8
2	Cook	🟩	🟫	🟫	🟨	🟫	🟫	🟩	🟩	🟩	🟩	🟩	🟩	🟢	🟩	3.6
3	Customer	🟢	🟧	🟫	🟢	🟫	🟨	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟢	3.4
4	Trader(shop)	🟨	🟨	🟫	🟨	🟫	🟩	🟢	🟢	🟢	🟩	🟢	🟢	🟢	🟢	3.5
5	Processor	🟩	🟩	🟨	🟢	🟩	🟩	🟩	🟢	🟢	🟢	🟢	🟢	🟩	🟢	4.4
6	Procurer[x]	🟩	🟩	🟢	🟢	🟩	🟢	🟫	🟨	🟨	🟢	🟩	🟩	🟩	🟨	4.0
7	Grower	🟩	🟩	🟩	🟩	🟩	🟨	🟫	🟫	🟫	🟩	🟢	🟢	🟨	🟧	3.5
8	Seed grower	🟢	🟨	🟩	🟨	🟢	🟧	🟫	🟫	🟫	🟩	🟨	🟨	🟨	🟫	2.7
9	Breeder	🟢	🟨	🟢	🟢	🟨	🟧	🟫	🟫	🟫	🟨	🟢	🟩	🟫	🟨	3.0
	Average	4.0	2.9	2.8	3.8	2.9	2.9	3.1	3.2	3.2	4.1	3.7	4.1	4.0	3.4	3.4

t Specifications of raw, finished and dish

u Quantity and quality of the raw material tubers going to factory

v Description and food value of the product

w New products on offer, wider range of products

x Procurement consists of agronomists assisting growers and informing factory, and also of agents contracting growers supply chain and have no actors below to give information to and in general, for fear of competition, they are not interested in sharing information with peers. So, the score awarded for the attribute “Desire to supply info downstream and to peers” is low (1). For consumers (eaters), there is no actor above them but they like to share experiences with pears and possibly with a dietician.

The map shows a dichotomy here and there with attributes b, c and e of special interest for producers and g, h and i for traders and users. Here, all actors keep the average of attributes well below 3.3, whereas meeting specifications, sharing information and environment-friendly production are important for most actors yielding averages of over 3.8. The average value of all attributes is the lowest for the seed growers and the eaters, 2.8 and less. Seed growers are not concerned about what the eaters think nor how (new) products look like. Consumers have no interest in all attributes regarding the raw material price, quality and availability. The processors have the highest average value of the scores of the attributes underpinning their central role in the chain.

A dendrogram (not shown) reveals that actors are divided into two distinct clusters (Table 3). One deals with the quantity and quality of the raw material from breeder to procurer and the other one the remainder. The eater is not very closely associated with the cook but takes a rather independent position as the consumer has no specifications to meet, does not store the products nor the dish made thereof and has less need to learn from peers than cooks do. The attributes have four groups around satisfaction, information, meeting specifications and supply of seed and raw.

The Performances Domains

Formulation of the Domains

In the previous section about the supply chain, the role of the actors growers and processors was described and their information requirements were made explicit. Here, the domain of performance is defined for growers as the yield and quality of the raw material they produce (value per unit area) and that of the processors defined as recovery of the highest value finished product from the raw material with minimal losses to lower value products (value per ton raw).

The task of cooks is to use products for the composition (C) of a dish or side dish as a meal component through preparation (P), heating (H) and arranging (A) taking into account societal aspects such as affordability: $C=P+H+A+S$. Product-depending preparation includes unwrapping, thawing, reconstitution and selection type of meal ingredient ranging from plain boiled tuber to complicated gratins. Heating, also product dependent, is through boiling (microwaving), frying or baking. This survey does not go into detail about the tasks of cooks but will discuss losses in kitchens and on the plate.

Condensation of the Field Performance Domain

All harvested tubers and their recovery-determining quality, the production of a field, are its yield (Y). It results from the genotype and seed tuber quality planted (G) in a particular environment with its climate and soil (E). Performance equally follows from farmer’s management practices supplying the soil with water and nutrients and protecting the crop. The ensemble is represented as $Y=G+E+M+S$ (Kropff et al. 1995; Haverkort 2018), summarized in Table 4 and subsequently elaborated. Devaux et al. (2021) used the same expression and discussed how breeding (earlier, resistant) by using new techniques (hybrid seed, genetic modification and gene editing), better seed quality, crop management (precision farming, decision support systems) and supply chain management (turn waste into value, reduce post-harvest losses) all lead to improved performance.

Yield

The expression of the performance of a crop is its yield (Haverkort and Struik 2015), expressed as t ha^{-1} fresh matter or dry matter and in the case of starch crops, their starch yield as t ha^{-1}. High dry matter yield means a high amount of finished processed products and as such is of socio-economic importance.

More irrigation, nitrogen and potassium fertilisation and earlier harvesting before crop maturity reduce dry matter (Haverkort et al. 2015). In general, the range is from 16 to 26% dry matter of tuber fresh matter. The protein concentration of about 2% of fresh matter is not much influenced by variety, growing conditions and farming methods. Variety hardly affects the mineral (Fe, Zn, K, Mn) concentrations but soils rich in certain minerals yield tubers with high concentrations of them, so does the supply of minerals through fertilisers strongly increase their concentrations in the tubers. Tubers of different varieties differ in vitamin concentrations from 15 to 45 mg per 100 g (Jea-sook Han et al. 2004) but hardly from altered growing conditions. The flesh colour of varieties is indicative of the quantity of flavonoids (red) or terpenoids (yellow) (Brown 2005), more expressed at lower temperatures and more intense solar radiation. Glycoalkaloid concentrations (TGA) are strongly variety dependent and tubers exposed to sunlight have higher concentrations than those buried deeper in the soil and higher levels of nitrogen fertilisation are associated with higher levels of TGA. In the USA, the legal maximum level of TGA in fresh potato is 20 mg per 100 g (USFDA 2021). Nitrate concentration in tubers is variety dependent and decreases in the tubers during the growing season so prematurely harvested tubers have the highest concentration. Tubers grown at high levels of soil nitrate levels also have higher nitrate levels in tubers. “Hungary has rules of 100 mg/kg as the maximum limit of solanine equivalents of raw, unpeeled potatoes. In Finland, a maximum level for glycoalkaloids in potatoes of 200 mg/kg exists. Denmark has a guideline of 200 mg GAs/kg for known potatoes varieties and 100 mg/kg for new potatoes types. The maximum acceptable concentration of potato tubers of 20 to 25 mg per 100 g fresh potato (equivalent to 200–250 mg/kg) has been set in the United States.” (EFSA 2022).

Not all tubers are marketable as it depends on the specifications of their destiny; 90% is assumed but it is 100% for starch and around 80% for crisping tubers (Halseth 2015) due to the elimination of odd sized tubers, defects and ones with too low specific gravity. Yields depend on the efficient use of resources of which approximations of optimal values are listed in Table 5.

Table 4 Aspects, examples and societal issues not exhaustive

Aspects		Examples	Societal relevance
Y	Yield Quality	Tubers t/ha fresh Tuber size Dry matter content	More efficient attainment of high yields and quality increases the recovery of finished products in the factory and assures a greater return on investment with minimal use of resources
G	Species *Solanum*	*S. andigena* (Peru) *S. phureja* (Colombia) *S. tuberosum* (global)	Different species evolved in different environments where people domesticated them by continuously selecting larger tubers with less undesired compounds (acrylamides)
	Variety	Frieslander (NL) Criolla (Colombia) Russet Burbank (USA)	Varieties within species are clones selected traditionally or in a breeding programme adapted to local biotic and abiotic growing conditions, taste and processing needs
	Propagation material	Seed tubers Cuttings, TPS Mini-tubers	The clonally multiplied tuber crop needs renewed stocks of healthy seed tubers derived from multiplication programmes increasingly using mini-tubers from in vitro and ex vitro cuttings
E	Altitude, latitude, soil	Highlands (Kenya) Summer (Europe) Winter (India) Spring and autumn (Tunisia)	Potato thrives not well at low nor high temperatures so farmers can grow year-round at tropical highlands and at lowlands in winter in the subtropics, in autumn and spring in dry summer climates and in temperate summers (soil conditions permitting)
M	Watering Fertilisation Protection	Rain and irrigation Manure, fertilisers Crop protection	The level of technology and availability of water, nutrients and chemicals to a great extent determine how farmers can optimize crop yield and quality so their subsistence and/or profitability
S	Environment Food safety	Resource use, emissions, residues	Producers and consumers want food to be produced in a sustainable way

Yield = Genotype + Environment + Management + Society ($Y = G + E + M + S$)

Table 5 Yield determining efficiencies (conversion factors) in raw material production (after Haverkort et al. 2015)

Resource	Use efficiency	Dimension	Optimal value	Main efficiency determining factors
Land	LUE	g/m^2	4500	Length of growing season, radiation, water
Marketable	MUE	g/g	0.90	Meeting market specifications
Radiation	RUE	g/MJ	1.25	Water availability
Water	WUE	g/L	6	Nitrogen availability
Nitrogen	NUE	g/g	200	Water availability
Biocides	BUE	g/g	2500[1]	Rainfall
Labour	LaUE	s/kg	1.68[1]	Yield (Land Use Efficiency)
Costs	CUE	€/kg	0.18[2]	Yield, rainfall, manure
Seed tubers	SUE	g/g	20	Yield
CO_2[3]	CUE	g/g	0.1	Yield, rainfall, storage conditions

[1] Haverkort 2018; [2] FAO 2021; [3] Haverkort and Hillier 2011

Genotype

The family of Solanaceae (nightshades) has many species (Machida-Hirano 2015), among them *Solanum tuberosum* adapted to long days and grown worldwide and also, many less widespread species are still occurring in South America such as the late maturing *S. andigena andigena* in Bolivia, Peru and Ecuador and the yellow fleshed *Solanum phureja* is still popular in Colombia and recently introduced into the variety packages in North America and Europe. The edible tuber-bearing species are just a few among the hundreds of wild species that were domesticated by the peoples that lived in the Andean highlands of South America. They selected tubers that were not too small and contained few bitter substances (glycoalkaloids; Johns and Alonso 1990) with lengths of growing and tuber dormancy periods that suited the dominant environment. From human aided natural selection in the Andes and through breeding programmes there and globally, varieties were produced that are liked by the consumers for taste, perform well in the given temperature window and resist the most common viral, fungal and bacterial diseases and the most common pests. Closely linked to the genotype planted is its propagation material, usually whole or cut seed tubers. Cuttings and mini-tubers play a role in the production of commercial seed tubers but in a few places, farmers plant rooted sprouts or stem cuttings as propagation material (Uyen and Vander Zaag 2008). Recently, several hybrid true potato seed breeding programmes aim at the use of botanical seed (true potato seed) to produce tubers from its seedlings for seed and/or consumer purposes.

Environment

With average day-night temperatures above 8 and below 28°C, the potato crop grows (Haverkort et al. 2015). Besides above-ground factors (the weather), below-ground factors are equally important, besides provision of nutrients, especially the potential depth of the rooting zone and the water holding capacity of this zone to assure an adequate supply of water from rain and/or irrigation (Haverkort 1990).

The four main processing potato-cropping environments are dry or rainy, summer or winter seasons (Table 6). Mediterranean climates also have spring and autumn crops but these have no processing quality. Winter seasons typically have a duration of 3 months and summer seasons of 6 months. With a projected (IPCC 2021) increase of atmospheric carbon dioxide from current 400 to future 600 ppm and a 2°C temperature increase by 2060, crops have a higher growth rate due to the 'fertilizing' effect of CO_2 (Jaggard et al. 2010) but heat-free winter seasons are shorter by a week and frost-free summer seasons longer by 3 weeks. Haverkort et al. (2013) and Franke et al. (2013), based on the LINTUL-POTATO model of Kooman and Haverkort (1994), calculated yield and water needs with daily weather of 1960 and 2050 in four contrasting South African environments. Table 6 shows a similar exercise with monthly weather data from NASA (2021) and Gaisma (2021) of four sites representing such environments. It is too warm to grow potatoes during about six days both at the start and the end of the winter season. The remainder of the season is about 1°C warmer than current. The yield effect of the lengthening of the summer growing season is more or less nullified by the increase of heatwaves during which crop growth halts.

As a result of increased CO_2 yields of winter crops increase by about 10% and of summer crops by about 20%. Yields of spring and autumn crops hardly increase as both move closer to winter with shorter and more cloudy days with reduced solar radiation. The water use efficiency of winter crops stays more or less the same but for summer crops it moves up for Europe for instance from 131 to 153 kg/mm. The amount of solar radiation to produce 1 t of fresh tubers decreases in all four situations. Van der Waals et al. (2013) calculated that with an increase in total

Table 6 Current and future average climate data over the growing season crop yields and evapotranspiration (ETP) in four contrasting growing environments

Property	Unit	Rainy winter		Dry winter		Rainy summer		Dry summer	
		South Africa		India		North Europe		West America	
		2020	2060	2020	2060	2020	2060	2020	2060
Radiation	MJ/m^2/day	15	15	20	20	25	20	30	30
Minimum temperature	°C	10	11	12	13	10	12	10	12
Maximum temperature	°C	24	25	24	25	21	23	28	30
Season length	Days	100	95	95	88	180	205	170	195
Evapo-transpiration	mm/season	200	220	500	550	600	660	1100	1200
Yield	t/ha	45	49	65	72	79	101	88	109
Radiation use	MJ/t × 1000	33.3	29.0	29.2	24.4	57.0	40.6	58.0	56.4
Water use	mm/t	4.4	4.5	7.7	7.6	7.6	6.5	12.5	11.0
NASA data		Cape Town		Ahmedabad		Lelystad		Pocatello	

temperature sum in summer, pest pressure increases as more generations will fit in one season, but that of late blight caused by the oomycete *Phytophthora infestans* decreases because of an increase in frequency of temperatures that are supra-optimal for its development. The projected yield levels do not take into account major occurrences of deleterious heat waves, droughts, floods and introduction of pests and diseases that reduce average levels nor do they make allowances for crop management practices aimed at increasing yields such as site selection, cooling the crops, draining water and adequate crop protection measures.

Management

Potato crops need to be planted in loose, friable soils and earthed up (hilled), supplied with water and nutrients and protected against prevailing pests, diseases and weeds. All these aspects of crop management involve intensive organisation and planning, use of labour, compost and manure in subsistence and low-input farming. In high-input farming, tractor-driven equipment and the use of chemicals (fertilisers and biocides) are deployed (Haverkort 2018). Further decisions taken by the grower regard selection of site, season, variety, seed quality, timing of operations, handling (grading and sorting), storage and marketing.

Condensation of the Factory Recovery Domain

The interface of the domains field and factory performance is made explicit in Table 7 which shows the product requirement and how G, E and M steer the processing qualities in the desired direction. Tubers destined for the production of starch need the highest dry matter concentration of which the major proportion consists of starch. Other variety requirements, besides disease resistance, are few as the tubers after washing in the factory are ground. Starch factories are found at sites where tuber production is at the lowest costs: rainfed summer crops yields with low input needs. Raw material for crisping needs the lowest concentration of reducing sugars as cooking in oil at relatively high temperatures for a prolonged period offers an optimal scope for the formation of acrylamide. Fluctuating temperatures and water supply during crop growth lead to high concentrations of reducing sugars that decrease towards crop maturity and during storage at low temperatures, less than 5°C (Seal et al. 2008). The protein concentration in general close to 2% of the tuber fresh matter is not an issue with most destinations but starch factories, except those producing food-grade protein, prefer a low protein:starch ratio.

The mineral concentrations are mainly determined by their soil concentrations, and health affecting compounds by variety. The major loss of weight of the raw material entering a processing facility is a consequence of the loss of water. Tubers or parts that are only boiled, packed and chilled lose no water. Fried and frozen products, fries and formed, retain a considerable proportion of the water present in the fresh tuber, about 78%, resulting in a recovery after peeling, blanching and frying of about 50% (Somsen 2004).

Table 7 Quality of raw material dependence on crop variety, surrounding conditions and cultivation practices

Quality classes	Product classes	Desired attribute	Issue	Genotype	Environment	Management
Dry matter concentration (DMC)	Starch	Highest	Starch varieties have the highest concentration (27%) followed by crisping varieties (23%). French fries raw material 21.5% and boiled chilled tubers around 20%	Apt variety	High DMC in temperate summer crops	Low nitrogen, potassium, irrigation, late harvest
	Chips	High				
	Flour	High				
	Frozen	Moderate				
	Chilled	Lowest				
Reducing sugars	Starch	No issue	Glucose and fructose cause product browning at frying, more so at higher temperatures and for a longer time so the issue is most prominent in crisping tubers but also causes sugar ends in French fries	Apt variety	Problem fluctuating moisture, temperature	Regular irrigation, cool crop, late harvest, warm storage
	Chips	Lowest				
	Flour	No issue				
	Frozen	Low				
	Chilled	No issue				
Protein	Starch	Lowest	To date, starch varieties were selected for low protein as they had low value as feed. Recently some factories extract food value protein and then prefer high concentrations	Starch varieties are low in protein	Temperate climate has the highest starch:protein ratio	High nitrogen
	Chips	No issue				
	Flour	No issue				
	Frozen	No issue				
	Chilled	No issue				

Table 7 (continued)

Quality classes	Product classes	Desired attribute	Issue	Genotype	Environment	Management
Minerals	All	No issue in starch	Potassium and phosphorus are assumed to be present in all products and to deliver food value	Hardly any influence	Influences K, Fe, Zn, Cu content	Influences K content mainly
Vitamins, Anti-oxidants	All	No issue in starch	Vitamin C, B, flavonoids, terpenoids and phenolics matter in chilled and frozen products	Strong variety influence	Hardly matters	Hardly matters

Dry products (chips, starch, flour) have the lowest recovery of about 25%. The market value is inversely proportional to the degree of recovery. Some mineral concentrations are reduced through leaching when boiling tubers in water especially when cut into pieces such as magnesium, zinc, manganese and particularly potassium over 50% reduction (Bethke and Jansky 2008). Concentrations of other minerals, such as calcium, are close to 10 mg per 100 g fresh weight boiled and unboiled but the concentrations increase with dehydration resulting in chips having concentrations close to 40 mg Ca/100 g fresh tubers (Bethke and Jansky 2008). The vitamin C concentration is about halved by boiling but the levels in dry products are about the same as in fresh uncooked tubers, considering that potato consists for over 75% of water; it implies that in dry products, about 75% of the ascorbic acid disappeared (Camire et al. 2009. The anti-oxidant chlorogenic acid–iron complex when in touch with oxygen oxidizes and gives processed potatoes a grey hue, so-called after cooking darkening, which in the factory is counteracted by soaking the slices or sticks in a solution of sodium acid pyrophosphate (SAPP) (Wang and Nowak 2004) that inactivates iron by chelating. The compound nitrate (dissolves in boiling water) and glycoalkaloids considered unhealthy disappear mostly when peeling and heating at processing.

Each product destiny × environment combination has its own range of cultivars. Starch needs late varieties making the best use of the available length of the growing season which also have a number of rustic characteristics such as some frost and late blight resistance, tolerance to intermittent dry spells and nematodes. Starch factories in general do not run year-round so storability is less of an issue. Factories producing fried products do run year-round so the varieties need an adequate dormancy period and should not accumulate reducing sugars.

Recovery and its components are deliberated in the following paragraphs.

Recovery

Recovery in potato processing is the weight of the finished product produced per ton of fresh tubers delivered to the factory as raw material, expressed as a fraction. For chips, this is about 25%, for starch 20% and for French fries 50%. When more tubers meet size specifications and when the raw material has a higher dry matter concentration, recovery is higher than from crops with a lower dry matter content, many tubers with an odd size and presenting defects. The recovery of a freshly harvested crop is less than that of the crop delivered to the factory because losses occur in post-harvest crop handling (H) and storage (S). Manufacturing products from the harvested tubers (the raw material), has as an aim, a high recovery: kg finished product per ton tubers harvested (R). This is realized through product-specific handling (H), storage (S) and processing (P) of the tubers and also considering matters of social interest such as attention given to spare the environment as was shown in Table 4. Together, they are represented as $R = H + St + P$, elaborated below and outlined in Table 8.

Table 8 Non-exhaustive aspects of "Recovery = Handling + Storage + Processing ($R = H + St + P$)"

	Classes of factory performance aspects	Examples (instances)	Societal relevance
R	Finished product	French fries	Farmers grow specific crops and processors make desired end products in a cascade, e.g. chips (end product), flakes (from slivers), feed (from peels) and waste water to the purification unit
	Byproduct	Flakes	
	Waste	Water treatment	
H	Tare removal	Sieving, washing	Consumers and processors need clean tubers without defects and of the right size as to reduce transport and losses in kitchen or factory
	Sorting	Removal of defects	
	Grading	Sizing to use	
S	Ambient	Temperature	Controlling the ambient conditions of tubers after harvest makes them available to users for a prolonged period after harvest and reduces losses
	Ventilated	Relative humidity	
	Refrigerated	Carbon dioxide	
P	Dehydration	Starch extraction	Potato derived products fulfil the needs of the industry as an excipient (filler starch), intermediate (pellets before expansion) or final consumer use as snack (chips), ingredients (flakes) or convenient replacement for home or restaurant preparation (French fries)
	Boiling	Flour production	
	Frying	Frozen French fries	
	Cooling	Hilling, freezing	

Handling

Sorting of tubers by eye on a (revolving) sorting table or by computer vision aided technology (Pedreschi et al. 2016; Bahadirov et al. 2020) involves the removal of unmarketable tubers (rotten, odd-shaped and tubers showing defects such as cuts). The incidence of diseases (bacteria and fungi) causes rotting when insufficiently controlled, fluctuation of temperatures and soil moisture during the growing season cause tuber regrowth, knobbiness, growth cracks, translucent ends, hollow hearts and other defects. Harvesting by how or machine causes cuts and also gnawing animals are a reason for defects. Grading through passing the tubers over grids with appropriate dimensions leads to sizing into desired classes according to the specifications of the customer. Very small tubers below 30 mm are disposed of or used as feed, the remainder sized according to what the customer specifies. Crisping factories require small round tubers, French fries factories need large oblong-shaped tubers and starch factories take all, including very small and defective ones. Handling does not influence the other tuber qualities such as the concentrations of dry matter, protein and other tuber constituents. On-farm post-harvest tuber treatments are aimed at delivering tubers fit to store and fit to deliver to customers, among them processing factories. Therefore, firstly, adhering soil is removed as it hampers the flow of air in ventilated stores (Rastovski and van Es 1985) and as little tare as possible is transported to the factory. On-farm washing of tubers is a less common practice but is substantial for the growers that deliver tubers to the crisping industry.

Storage

Only a part of the tubers goes to the customer ex-field without being stored for a predetermined period ranging from a few days for an early delivery to the factory, up to 5 months in regions with two growing seasons per year and up to some 11 months where there is only a single growing season. Tubers stored in bags, boxes or bulk produce heat, moisture, ethylene and CO_2 which need to be evacuated through ventilation (Eltawil et al. 2006); excess heat requires refrigeration at lower temperatures when storing for a longer period. Adequate storage management reduces losses through respiration, evaporation and rotting and assures a regular year-round supply of raw material. At ambient conditions, the temperature is the main limiting factor and in heap, storage usually does not exceed 1 or 2 months. With ventilation to evacuate built-up heat and moisture, this period is extended especially when combined with refrigeration to reduce respiration and the formation of carbon dioxide. If a sprout suppressant is applied (Paul et al. 2016), the total storage period is up to 11 months allowing a factory (with some leeway in harvesting) to run year-round. Storing tubers takes place temporarily on a heap in the field protected from rain and sunshine or for a longer period in purpose-built buildings in bags, boxes or bulk with forced ventilation and where needed forged refrigeration. Losses in storage are due to three factors, the main one being the evaporation of water through the skin of the tuber (Emragi et al. 2021). Evaporation is higher when the temperature of the tubers is higher and the relative humidity surrounding them is lower. The frequency and intensity of ventilation and the inlet air temperature regulate the two key aspects to reduce losses. The dry matter concentration of the tubers during storage increases when evaporation surpasses respiration (at low temperatures) and decreases when respiration is considerable at high temperatures and high relative humidity. Losses also occur due to rotting because of diseases such as late blight and bacterial wilt or because of physical damage and freezing. Storing at very low temperatures for a destination and too high CO_2 concentrations causes an increase in reducing sugars (Mazza and Siemens 1990) leading to dark coloured products at frying, reason why seed tubers are stored at 3°C, tubers for frozen fries at 6°C and for chips at 9°C because at higher temperatures, reducing sugars formed from starch disappear through respiration. Prolonged storage for several months leads to a decrease in the concentrations of beneficial vitamin C and detrimental nitrate and chlorogenic acid. When tubers are exposed to light, greening occurs and with it, an increase in glycoalkaloids concentration (Haruko Okamoto et al. 2020); similarly, concentrations increase when tubers sprout (Sengul et al. 2004).

Processing

Processing is aimed at products that add value to the raw material. Cold processes yield native starch that, when used for human consumption, either or not after chemical or physical transformation, needs to be heated in water. Heat treatments consist of blanching, steaming, microwaving, boiling and frying. Fried moist products reach consumers chilled or frozen. Boiled tuber parts are sold chilled or dried and ground (powder), and all processes underlying operations in factories are treated in Survey 2 (Haverkort et al. 2022b); Haverkort et al. (2022a, b, c) and Somsen (2004) modelled the proportion recovery they called the ‘yield index’ of French fries as a function of average tuber weight expressed as tuber number per kilogram, dry matter concentration and tuber shape (length, width, height) and losses resulting from peeling, slivers (too thin strips) and nubbins (too short strips). Larger tubers with a higher dry matter concentration have a higher yield index due to reduced losses, also of water evaporated.

Quantification of the Performances Domains

The 19 performance indicators, including the suitability of raw material for the production of starch, chips, flour, frozen French fries and chilled products and 11 attributes, are listed as a heatmap in Table 9. The heatmap shows a predominance of red colour, indicative of a minor influence of attributes on constituents such as minerals, vitamins and antioxidants, a moderate influence on the products made of tubers and a relatively strong influence on crop characteristics with green dominating. The columns show that variety and processing influence virtually all crop performance indicators but seed and crop protection only targets

Table 9 Heatmap of the 19 classes of performance and the degree the 11 attributes influence them

🟩 🟢 🟨 🟧 🟫

Strong influence	a	Variety	Minor influence
	b	Seed	
	c	Climate	
	d	Soil	
	e	Rain/irrigation	
	f	Fertilisation	
	g	Crop protection	
	h	Defoliation of the crop before lifting	
	i	Handling (grading, sorting)	
	j	Storage	
	k	Processing affecting contents and yields	

#	Classes of performance of field and factory production	Geno-type		Environment			Manage-ment			Recovery			
		a	b	c	d	e	f	g	h	i	j	k	Av.
1	Crop duration	🟩	🟢	🟩	🟫	🟩	🟢	🟩	🟩	🟫	🟨	🟫	3.5
2	Yield delivered to factory	🟩	🟢	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟢	🟫	4.3
3	Tare	🟧	🟫	🟢	🟩	🟩	🟫	🟫	🟫	🟩	🟫	🟫	2.5
4	Harvestable period	🟨	🟧	🟩	🟩	🟩	🟫	🟫	🟩	🟫	🟩	🟫	3.1
5	Dry matter concentration	🟩	🟧	🟩	🟢	🟩	🟢	🟨	🟢	🟫	🟨	🟩	3.7
6	Tuber size	🟩	🟢	🟢	🟧	🟩	🟢	🟫	🟨	🟩	🟫	🟫	3.2
7	Protein content	🟢	🟫	🟨	🟫	🟫	🟢	🟫	🟫	🟫	🟫	🟩	2.1
8	Reducing sugars content	🟢	🟨	🟢	🟫	🟫	🟧	🟫	🟢	🟫	🟩	🟩	2.8
9	Proportion of defects	🟨	🟫	🟢	🟢	🟫	🟨	🟫	🟨	🟩	🟨	🟫	3.0
10	Minerals content	🟢	🟫	🟫	🟩	🟫	🟩	🟫	🟫	🟫	🟫	🟩	2.4
11	Vitamins content	🟨	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟨	🟩	1.7
12	Antioxidants content	🟩	🟫	🟢	🟫	🟫	🟫	🟫	🟫	🟫	🟫	🟩	2.0
13	Glycoalkaloids content	🟩	🟫	🟨	🟫	🟫	🟫	🟫	🟨	🟫	🟫	🟩	2.1
14	Nitrate content	🟢	🟫	🟫	🟨	🟫	🟩	🟫	🟨	🟫	🟨	🟩	2.5
15	Starch yield	🟩	🟫	🟩	🟧	🟧	🟨	🟨	🟫	🟫	🟧	🟩	2.7
16	Chips yield	🟩	🟨	🟩	🟨	🟨	🟢	🟢	🟨	🟩	🟩	🟩	4.1
17	Flour yield	🟨	🟫	🟧	🟨	🟧	🟧	🟨	🟨	🟨	🟨	🟩	2.7
18	Frozen French fries yield	🟩	🟨	🟩	🟨	🟨	🟢	🟢	🟨	🟩	🟩	🟩	4.1
19	Chilled products yield	🟨	🟧	🟨	🟨	🟧	🟨	🟨	🟨	🟢	🟨	🟩	3.5
	Average	4.1	1.9	3.6	2.7	2.6	3.0	2.2	2.8	2.5	2.8	3.9	2.9

a few. The vitamin content is least affected by the attributes with an average score of 1.7. There is only a slight difference between varieties but processing does influence the concentration of vitamins (Survey 4, Haverkort et al. 2022c). Many attributes exert an influence on deliverable yield to the factory; hence, its highest average score of 4.3. Products requiring many specifications, chips and French fries for the same reasons also receive average scores of above 4.

The lowest average of an attribute is the influence of seed on the classes, a value of 1.9. Seed quality (size, age, health) only wields influence on crop duration and yield; this also holds for crop protection for the same reasons and the weather and fertilisation to a somewhat lesser degree. Variety and processing affect many classes both scoring close to 4 on average.

Resource Use in Factories Domain

Formulation of the Resource Use Domain

Efficiency is defined as the amount of resource input per weight unit finished product and is optimized by avoidance of losses and unwanted emissions. For processing potato, this domain is delimited by the production of the tubers as raw material on farms and the manufacturing of finished products. Resources in tuber production as illustrations are land, water and fertilisers and in processing energy and water mainly. Productivity then is t/ha tuber (or kg/m^2), m^3 water/t on farms and GJ/t French fries in factories. Losses reduce these figures and avoidance of losses increases them. Examples of (partly) avoidable losses on farms are tubers left in the soil at harvest and weight loss in stores. At processing, sorting of washed, peeled and processed tubers with defects creates losses. These are partly avoidable by altering operations (trimming) and or criteria (accepting shorter French fries) and using rejects as raw material for alternative high-value products such as flakes.

Cluster analysis demonstrates three clusters of classes, one centred around the crop, one around recovery and dry matter and one focusing on the concentration of components. Of the attributes, processing stands alone and variety and environment are closely related twins exerting similarly affecting classes and so are seed and crop protection, crop duration and yield.

Condensation of the Resource Use Domain

Resource Use in Processing Tubers

At the turn of this century interest in the use of land, water and energy in growing, processing and preparing tubers grew, resulting in the data of three groups of researchers with a focus on the situation in the UK as represented in Table 10. The amount of energy to grow 1 kg of tubers was calculated at 1.3 MJ, equivalent to 97 g CO_2 grown on 0.22 m^2 so 45 t/ha with fuel for traction, electricity for cooling and energy embedded in fertiliser production as the three main components. Haverkort and Hillier (2011) and Baltussen et al. (2016) calculated respectively 77 and 65 g CO_2 per kg tubers as yield levels (somewhat lower in the UK than in the Netherlands), definitions, systematics and system boundaries differ. More precise life cycle analyses by, among others, Swiss researchers (e.g., Walker et al. 2018) yielded more consistent data, also more in line with those of Haverkort and Hillier (2011) and Baltussen et al. (2016). Mattson and Wallen (2003) and Haverkort and Hillier (2011) calculated a somewhat higher figure for organic production where no chemicals are involved but more energy is spent on transport of manure, machinery and cooling

Table 10 Early reports on energy use in potato production, processing and preparation. Based on Williams et al. (2006)[1], Mattson and Wallen (2003)[2], Foster et al. (2006)[3]. Headings in bold pertain to the rows below them

Per 1 kg raw potato stored[1] (Williams et al. 2006)	Data	Per 1 kg peeled and prepared	MJ	% of 4.5 MJ
Energy MJ	1.3	Cultivation	0.6	13
CO_2 equivalent g	97	Storage and cooling	0.5	11
Pesticides dose g	4.4	Transport to packer	0.2	4
Land use ha	0.000022	Packing	0.6	14
Energy breakdown[2]	**% of total**	Transport to retail	0.55	12
Field diesel	28	Retail	0.2	4
Machine manufacturing	8	Transport to home	0.65	14
Crop storage and cooling	36	Household use	1.2	28
Fertiliser manufacturing	24	TOTAL	4.5	100
Pesticide manufacturing	3.9			
		Finished product[3]		
		kg French fries	**5****	
		kg flakes	**36****	

**Inferred from gas use and production data of a pollution prevention and control factory founding permit

than for conventional growing of tubers. Boiled potatoes for household consumption represent 4.5 MJ/kg with cultivation and storage taking 24%, transport and trade 34% and bringing tubers home and cooking them 42%. Factory production of flakes was calculated at 5 MJ/kg and for flakes at 36 MJ/kg (Table 10).

Walker et al. (2018) calculated the energy and water use for the production of 1 kg of frozen French fries: 3.3 MJ thermal energy for steam peeling, blanching and frying and electricity for transport, sorting, grading and freezing totaling. West et al. (2020) calculated decarbonisation options for the Netherlands potato-processing industry, enumerated the processes involved in producing frozen French fries and flakes, their aims, methods and kind of material loss that maximally reach 10% per process (peeling, sorting, blanching). The energy in processing French fries was from electricity for transport, washing, grading, sorting, cooling and packaging, from steam (natural gas heated) for peeling and blanching and fuel (natural gas) for frying. These data are shown in Table 11.

The figure of 3.3 MJ/kg (GJ/t) is less than the 4.84 from Walker et al. (2018) because West et al. (2020) took the reuse of energy and decarbonized energy into account (Table 12). The data in Table 11 also show water use and material losses: 1 kg loss of two kg of raw material started with grading, peeling, blanching and frying French fries. The flakes data are also shown: it takes 6 times more energy to produce flakes than French fries. Here, some remarks apply: the French fries data do not include the energy embedded in the oil present in the finished product and for French fries production, much less water is evaporated (at the cost of energy) from the product (weight loss in blanching and frying is 0.33 t of the 2 t of raw material (16.5%) against 3.9 t weight loss of 5.1 t raw from the start (76.5%)). Looking at it

Table 11 Energy and water use and material loss to produce 1 t of frozen French fries and flakes

Classes of processes	Frozen French fries (2 t raw)			Flakes (5.1 t raw)		
	Energy (GJ)	Water use (L)	Weight loss (t)	Energy GJ	Water use (L)	Weight loss (t)
Grading and sorting Washing	0.0023 E	13000	0.11	0.018 E	33035	
Peeling, trimming	0.47 S	265	0.24	1.5 S	762	0.2
Cutting or slicing	0.0004 E		0.03	0.068 E		
Sorting	0.0004 E		0.02			
Blanching	0.001 E 0.29 S	333	0.01	0.034 E 5.1 S		
Drum drying				0.085 E 13.0 S		3.9
Frying	0.02 E 2.13 F	0	0.59			
Cooling				0.02 E		
Freezing	0.35 E	0	0			
Packaging	0.01 E	0	0	0.01 E		
Refrigeration	0.01 E					
Total/t finished	3.2837	1895	1.0	19.835	35710	4.1

E electricity, *F* fuel, *S* steam (West et al. 2020). Notes: Mass of potato products excludes packaging. It is assumed that chilled potato products processing consumes the same amount of energy, minus the freezing energy use, and that chips production excludes both freezing and refrigeration. Source: West et al. (2020) (Adapted from Walker et al. 2018; Masanet et al. 2008; and Rijksdienst voor Ondernemend Nederland 2016)

from the perspective of raw to make finished products, 1.65 GJ/t for French fries and 3.88 GJ/t for making flakes which reflects the reality that to make flakes twice as much water needs to be evaporated from a kilogram of raw material. Chips production does not need cooling nor freezing thereby saving 0.373 MJ/kg but evaporating water is at higher costs, comparable to dehydrating to produce flakes at 19.8 MJ/kg. A further reduction in CO_2 emission from electricity and gas use in the Netherlands as proposed by the TNO report (West et al. 2020) is shown in Table 12, reduction of fossil fuel and reduction of loss of potato mass through optimized procedures for peeling, sorting and blanching. Energy-saving options include improved equipment in steam peeling and cooling, heat recovery and deploying microwaves and pulsed electric fields. Other sources of energy also lead to less CO_2 emissions such as biogas, hydrogen and geothermal energy and the use of more electricity from part renewable sources where hitherto fossil fuel is used.

Losses and Wastes

Not all material that grows in the field that is lifted, traded, processed and prepared is consumed as some is lost, wasted or given another destination in side flows. Table 13 shows these, among others based on Baltussen et al. (2016) and Mouron

Table 12 Options for decarbonisation: energy efficiency, material efficiency and energy source (West et al. 2020)

Energy	Options
Steam peeling	More efficient design saves energy and reduces peel losses. Heat recovery
Pre-heating	Through pulse electric field (PEF) rather than thermal
Blanching	Microwaves costs less energy and less water, infrared combined with heating and closed loop blanching saving water and energy
Frying	Inserting hot oil at various stages of frying (multi-flow injection), heat recovery for drying and pre-heating
Chilling and freezing	More efficient (compressors, condensors) mechanical freezing, changed refrigerants, (ammonia), re-use heat from pumps
Material	
Peeling	Abrasive peeling has less skin loss but requires more capital and water
Sorting	Intelligent optical sorters prior to peeling reduce losses from over-peeling
Blanching	Steam blanching causes less leaching of nutrients from slices but requires more energy
Source	
Biogas (own)	Produced by the factory from waste water and solid tuber parts (skin)
Biogas (bought)	Purchased from companies deploying anaerobic digestion of plants or gasification of wood
Electrification	Use electricity (lower CO_2 emission than gas) to produce heat for steam, water and frying
Hydrogen	Hydrogen used to fuel boilers, provided it is produced with renewable electricity
Geothermal	Injecting cold water to 4-km depth and extracting hot (130°C) water

et al. (2016). Losses in the field concern small unharvested tubers dropped between bars of sieves, tubers too deep for the digger, cut tubers and bruised tubers when harvested under too dry conditions. Pre-storage sorting eliminates defects and rots and post-storage pre-delivery-eliminated sizes and shapes not meeting specifications of traders or processors. Losses during storage are due to water loss, shrinkage mainly. Leftover seed tubers if not treated with fungicides are used as feed for cattle, same as tuber lots that show many rotten tubers or are completely sprouted. This is exceptional when lots are intended for processing and shows some calamity took place in the store. When arriving at packing stations, ex-field tare is collected there. Leftover fresh tubers in retail because of green colouration or sprouting become feed. Rejected truckloads because of excess defects or too low dry matter (floaters in brine) become feed, same as with peels, slivers (if not turned into flakes) and rejected par-fried products among others because of sugar ends. Leftover oil after use for frying for some time is turned into biofuel. Reported losses per stage vary widely among the eight literature sources consulted, partly due to inaccurate boundaries (for instance sorting by farmers or by traders, not all sources include processing) and their definitions, but also where (Europe, Germany, EU, Switzerland UK, USA, worldwide) and how (interviews, surveys, measurements, mass flow analysis) the data were collected. The mean value of the eight sources shown in Table 13, therefore, is only taken from at least 4 sources with unambiguous data. wwTraders

Table 13 Losses, wastes and side flows in subsequent stages of tubers and products and their destination. Partly after Baltussen et al. (2011) and Mouron et al. (2016), more exhaustive personal observations added

Stage	Material	Definition	Destination
Farm	Foliage	Stems, leaves 3 t/ha	Stays in the field
	Seed tubers	Surplus not planted	If untreated feed
	Tubers	Not harvested or damaged at harvest	Remain in soil or are partly lifted
	Tare	Adhering soil, stones and plant parts	Remain on farm return to field
	Sorting, grading	Tubers with defects or of size not meeting market demands	Feed
	Rejected tuber lots	Rotted or sprouted lots	Exceptional situation, feed
	Unsold	End of season surplus	Feed, or to factory for flakes
Trade and packing	Washing water	Remains after washing tubers	Sanitation, cleaning recycling
	Tare	Adhering soil, stones	Returns to farms
	Rejects	Sorted tubers	Feed
	Past date	Not sold in time in retail outlets	Feed
	Transport	Tubers to factory, products to shop	Some damage
Processing	Rejected tuber lots	Truckload rejected, floaters	Feed, flakes
	Washing water	Remains after washing tubers	Sanitation
	Tare	Adhering soil stones	
	Starch	In processing water (from cutting)	Reclaimed, purified, modified
	Slivers	Too small cuts to make product	Flakes, feed
	Rejected par-fried	Products not meeting specifications	Feed
	Oil	Residual oil after replacement	Biofuel
	Fat crumbs and batter	Retrieved at sieving frying oil	Feed and pet-food
	Peels (steam, raw)	Peels released at steam and abrasive peeling	Feed (steam for non-ruminants, raw for ruminants)
	Processing water	Used in cutting and blanching	Treated (biogas, struvite)

Table 13 (continued)

Stage	Material	Definition	Destination
Kitchen	Oil	After frying	Waste
	Unused fresh produce	Unsuitable (green, sprouted)	Organic waste, substantial
	Unused frozen produce	(Small) portions left over	Organic waste, not substantial
	Not consumed	After preparation	Organic waste
	Packing material	Cartons, polythene	Plastic/paper waste
	Past date	Waited too long in pantry	Organic waste

wwwremove rejects (sorting) and unwanted sizes (grading) with destination feed or flakes. The losses at processing are elaborated in Tables 11 (West et al. 2020) and 13 (Baltussen et al. 2016). Definitions and boundaries here are not clearly defined by the authors. When the proportion of lost weight is reported with definition, recovery ‘losses’ are 50% with 500 kg French fries recovered from 1 t of fresh tubers but less than 20% on dry matter basis. More often than not, processors do not procure raw material through wholesale trade, so losses due to sorting and grading are then not allocated to ‘Processing’ but to ‘Trade’. Losses in kitchens of fresh tubers (WRAP 2012) are due to rejection of tubers following greening, rot, skin blemishes and sprouting. Products do not suffer from such rejections but have in common that not all prepared are consumed with leftovers in the pot and on the plate.

By far the greatest proportion of losses are reported for the kitchen, be it at homes or in outlets such as restaurants and institutions. According to Betz et al. (2015) and Willersinn et al. (2015), losses at retail and home are similar to those out-of-home. Losses in kitchens are due to tubers never prepared because of rejection (green, rotten, sprouted, skin blemishes due to, among others, silver scurf; WRAP 2012), losses during preparation and wasted after cooking (unemptied pots and plates). Most material wasted in kitchens is organic waste and becomes compost or biogas such as fresh tubers and products not prepared and meal components not consumed after preparation. Cooking oil, when not collected by supermarket chains, is wasted and burnt.

Mouron et al. (2016) analysed the Swiss potato supply chain assuming that 1 kg of French fries uses 1.84 kg of fresh tubers and identified for each stage a few hotspots where the industry could make strides to reduce losses to the environment in terms of non-renewable energy at the cost of CO_2 emissions contributing to global warming and terrestrial and aquatic ecotoxicity (Table 14). Production of tubers and oil for frying requires fertilisers that negatively impact terrestrial ecotoxicity. Making and deploying machines require fuel. Their fumes and also those of transport affect human health. Wastewater from washing tubers is withdrawn from and affects surface waters. Lighting in stores causes greening of tubers accompanied by the formation of glycoalkaloids. The origin of the frying oil matters as canola and sunflower have high scores on ecotoxicity because of the use of biocides. Palm trees to produce palm oil are low on renewable energy while high on CO_2 emissions and loss of biodiversity. Improvement of the efficiency of fertilisers, machinery, transport electricity for cooling tubers and products and frying in the kitchen, use, origin and production of frying oil and gas for steam peeling would have the greatest reducing effect on the negative environmental impacts. Mouron et al. (2016) reported that including frying French fries by the cook, 41 MJ of energy was spent on 1 kg, 25 MJ in the household, most of it represented in the canola oil used for frying, 10 MJ in the factory and 6 MJ on the farm and transport, five times more than boiled tubers on the plate and at the cost of more than 4 times the amount of CO_2 emission. Water use in the factory was 18 l per kg of French fries. Assuming that 50 t/ha potato yield requires 500 mm of water and 2 kg of tubers are needed to produce 1 kg of French fries, field production requires another 20 l of water from rain and irrigation (Haverkort et al. 2015). Loss of tuber and product mass at the various stages has received attention of the sources mentioned in Table 14. On-farm average losses

Table 14 Losses in the supply chain and kitchen (Mouron et al. 2016) following a particular case. The mean value of percentage losses in the various stages in industry and kitchen is based on the average value provided by 8 authors in different countries

Stage	kg loss	Losses due to	Hotspots	Impacting	Mean% loss
Farm, storage, grading	0.47	Rejects, water	Fertilisation	Aquatic and terrestrial ecotoxicity	19
			Machinery use	Energy, human toxicity	
Wholesale (trade)	0.11	Grading sorting	Transportation	Energy, human toxicity	7
			Electricity for cooling	Energy	
Processing	0.22	Water, rejects	Waste water washing tubers	Aquatic toxicity	17 ‘process often ill defined’
			Natural gas steam peeling	Energy, non-renewable, CO_2	
			Heating frying oil	Energy, non-renewable, CO_2	
			Frying oil	Terrestrial ecotoxicity	
Retail	0	None	Electricity for cooling, lighting	Energy, human toxicity	1
Kitchen Home, resto	0.04	Frying	Frying oil	Terrestrial ecotoxicity	32
			Electricity for frying	Energy, CO_2	

*Betz et al. (2015); Caldeira et al. (2018); Gustavsson et al. (2011); Kantor et al. (1997); Kranert et al. (2012); Mouron et al. (2016); Willersinn et al. (2015);WRAP (2012) reported were 19% due to harvesting in too dry conditions leading to bruised tubers, shrinkage during storage and removal of odd-sized tubers. Losses in trade following grading and sorting were 17% and in processing (often not well-defined) were 17% due to rejected intermediate of finished products but the bulk of losses was reported in kitchens of restaurants, caterers and households of products never prepared or not consumed. Hotspots identified concerned operations, processes and substances at the stages of production and their impact on ecotoxicity, energy use and CO_2 emissions. Fertilisers and wastewater affect water quality, machines and transport produce fumes, electricity for cooling (and frying in kitchens) requires energy, nonrenewable fuels emit CO_2, and frying oil (canola, sunflower) production is associated with terrestrial ecotoxicity from biocides and fertilisers. Reducing the environmental impact of the production and preparation of frozen French fries according to the authors needs to focus on these hotspots.

The hotspots indicated in Table 14 are divided into six themes: (1) soil health, fertility, water holding capacity and conservation, (2) water use, availability and quality, (3) energy use as electricity and fuel and embedded in chemicals, (4) mineral balance, availability and reducing leaching through green manure, (5) biodiversity and environment with effects of land use, emissions, and (6) human health with emphasis on residues of biocides and diets. Table 15 recaps the decarbonisation options (from Table 12), losses (Table 13) and among others showing directions of solutions to the issues raised in the hotspots of Table 14 but accentuates matters regarding production of raw material. Solutions regarding soil include control of soil-borne pests and diseases through crop rotation (affecting soil availability) and variety resistance management and maintaining or improving soil quality by enhancing soil organic matter content and avoiding salinity, erosion and stoniness. Crop growth requires water from rain and/or irrigation from surface water, dams or deep wells. Its impact is reduced by adjusting demand and supply, assuring water is replenished from local rainfall or at the source. Avoidance of salinity at fields near coasts and improving soil water holding capacity through soil depth and organic matter content, have an effect on water availability for crops. Energy savings in raw material production (also Haverkort and Hillier 2011) are realisable through regulating fertilisers, especially nitrogen, fuel in machinery and electricity for water pumping and cooling. Handling minerals is through avoidance of leaching, practising nutrient balances, assuring availability of potassium as potato especially needs this element and avoidance of leaching of nitrate by employing green manure. The habitat is spared by avoiding cropping and biocides in vulnerable areas and reduction of emissions to soil, water and air of gases, biocides and minerals. Biocides affect growers and nearby residents of applied fields less when deployment follows regulations aimed at safety and users of finished products take GAP-directed maximum residue levels (MRLs) into account. Canali et al. (2014) in their extensive study reported in "Drivers of current food waste generation, threats of future increase and opportunities for reduction in their extensive" distinguished three context categories, technological, institutional (divided into economic and legal aspects) and social (consumer behaviour and lifestyles). In the supply chain, they distinguished the links primary production, processing of agricultural staples, food processing and packaging, wholesale and logistics retail and markets, food services and households. For drivers of food wastes current, future worsening wand future

Table 15 Options to reduce the impact of processing potatoes on soil, water, energy, minerals use and health. Baltussen et al. (2016) as starting point and elements of previous tables and surveys

Stage	Soil	Water	Energy	Minerals	Biodiversity/environment	Health
Production raw (this Survey 3)	Health, nematodes, bacteria	Availability, origin surface, deep wells	Fuel (field operations)	P nutrient balance	Land use	Biocides
	Fertility, organic Matter	Restrictions, DSS irrigation	Electricity (storage, pumping)	N nutrient balance	Biocides	Sprouting inhibitors
	Availability	Quality (health, salinity)	In fertilisers	K availability	Emissions	
	Erosion, salinity stoniness	Water holding capacity soil	In biocides	Green manure		
Processing (Survey 2)	Tare Waste water	Closed cycle Use and sanitation	Fuel for frying Electricity for cooling	In waste water, recovery of P	Gaseous emissions	Residues, MRL
Kitchen (Survey 1)		Washing	Cooking	Organic waste	Waste separation	Diet, unhealthy calories, baby food, gluten free

Table 16 Current and future contributors (+) and opponents (-) of waste of potato products in the various segments of the supply chain in different context categories (after Canali et al. 2014)

Segments	Drivers*	Context categories			
		Technological	Institutional		Social (consumer behaviour and lifestyles
			Business and economy	Legislation and policies	
Primary production	Current	Storage	Supply/demand not well-tuned	Tax / subsidies for growers	Consumer preference
	Future +	Climate change with storage challenges	Customer demand less well known	Contracts supplier-retailer	-
	Future -	Genetics delivery of robust varieties	Shorter supply chain, better info exchange	Subsidy anti-food waste, more expensive primary production	Consumer awareness, information
Processing of agricultural staples (lumped with primary production)					
Food processing, packaging	Current	Planning supply raw	Contracts agreements	Low-cost food, externalities not charged	Consumer preference
	Future +	Not meeting specifications (climate)	Customer demand	Low disposal costs	Increased demand processed food
	Future -	Use all parts, automation	Awareness of food waste, information	Subsidy R&D	Increased demand processed food
Wholesale and logistics (lumped with food processing)					
Retail and markets	Current	Customer knowledge	Information sharing	Marketing standards	Behaviour, tools
	Future +	Reduced shelf life (not frozen)	Marketing strategies	Low costs waste disposal	Consumer preference and attitude
	Future -	Inventory management	Awareness food waste	Sanctioning waste inductions	Consumer awareness and attitude

Table 16 (continued)

Segments	Drivers*	Context categories			
		Technological	Institutional		Social (consumer behaviour and lifestyles
			Business and economy	Legislation and policies	
Food services: losses in retail and household are similar to those in other outlets (restaurants, caterers) so this link also becomes redundant					
Kitchen (of food services and households)	Current	Cooling	Low prices = waste easier	Waste collection policy	Attitude, behaviour
	Future +	Health drivers (perishability)	More leftover, increased variety	Food laws not taking waste into account	Affluence, small portions/ households
	Future -	Appliances	Doggy bag, awareness	Waste collection, dietary guidance	Initiatives on awareness and innovations

*Drivers of food wastes are the ‘Current’ ones, the ones increasing them ‘Future + ’ and decreasing them ‘Future -’

improving scenarios were selected. This matrix is shown in Table 16. The potato-processing industry from farm to fork does some on-farm processing such as storage, grading and sorting and in Table 16, these activities are assumed to pertain to primary production. The processing industry most often deals directly with farmers and with retail so the wholesale and logistics link coincides with food processing. The two links food services (restaurants, institutions and caterers) and households are lumped assuming that total losses are similar for both 'Kitchens' but the context content of both is considered in Table 16. There are a few recurring issues as a common denominator across chains, drivers and context. These are poor communication about supply and demand with current flaws and also hint at better communication that contributes to solutions. Government policies on subsidies and taxing of growers and actors in the supply chain segment disposing of waste and on enhancing awareness and R&D are considered essential contributors to drivers of food waste. Consumer preference for how food is produced and the potential to reduce waste is brought up a few times by Canali et al. (2014) and Aramyan and Valeva (2016) as is the low cost of production, processing and distribution.

Losses occurring from primary production to kitchens of outlets and households are driven at the current level and get worse or improve in future in technological, economic, legal and social contexts (Table 16). Across links and contexts, current flaws in communication lead to losses but future developments contribute to solutions, awareness of losses being a main aspect with government interventions through taxation, subsidies and research and development key as to make food more expensive by including externalities and so inviting consumers to waste less as it will be increasingly costly. Losses are greater in fresh produce due to their perishability compared to chilled and especially frozen products that have a longer life on the shelf and in cold compartments of pantries.

At higher cost of production and sales, increased prices would reduce food losses as consumers would consider it a financial waste. Including externalities (costs of avoidance of emissions and of the use of non-renewable resources) makes products substantially more costly and so contributes to future reduction of food losses. An increased awareness of the issues regarding food waste as a waste of resources land, water and clean air, besides financial aspects, as ethical dilemmas is considered an important contributor to diminished food waste. The report was not specifically aimed at fresh nor processed (packed, dried, chilled, canned, frozen) products but as generic to include all foods. So many of the issues raised do not pertain to chilled, frozen and dry potato products where perishability is less of an issue than is the case with fresh vegetables exposed on shelves. For processed products, planning is not a major issue; it is more imminent for fresh vegetables than for frozen French fries which can be stored for up to 24 months.

Quantification of the Resource Use Domain

Quantification of Impact on Habitat

Yield production of raw and subsequent manufacturing, so growing, handling storage and processing are associated with environmental concerns. Soil health is not affected by most operations but biocides have residual effects. Irrigation affects soil fertility through leaching of minerals but field operations compacting soils have a stronger effect. Freshwater as a resource is mainly withdrawn from the environment for irrigation and washing. Fuel leading to CO_2 emission and particulate matter (eco-toxic) is deployed in many operations and so is electricity. Decarbonisation opportunities are few for irrigation but for transport use of renewable electricity sources is opportune. Eco-toxic substances are nutrients from fertilisers, biocides for crop protection and fine particles from diesel fuel (tractors and lorries). Biodiversity is affected by most field operations and humans' health by crop protection and anti-sprouting chemicals and particulate matters and some side effects of frying in kitchens such as the formation of acrylamide.

The operations on farms traction and supplying resources, storage and mechanical operations such as conveying, grading and sorting that are shared with manufacturing, transport and temperature-related operations in factories as expressed in Tables 10, 11, and 12 are grouped into 10 rows in Table 17 with nine columns with attributes embodying their direct or indirect effect on the habitat. Many operations

Table 17 Heatmap of 10 classes of operations and 9 attributes about negative impact on environment and society (habitat)

🟩	🟢	🟨	🟧	🟫

Much			Little
	a	Soil fertility affected	
	b	Soil health affected	
	c	Quantity of water needed	
	d	Energy from fuel needed	
	e	Energy from electricity needed	
	f	Lacking decarbonisation opportunities	
	g	Eco-toxicity at risk	
	h	Biodiversity at risk	
	i	Human health at risk	

Classes of operations			a	b	c	d	e	f	g	h	i	Av
1	Growing	Irrigating	🟧	🟧	🟩	🟢	🟩	🟢	🟨	🟢	🟫	3.3
2		Fertilisation[m], organic matter	🟨	🟧	🟫	🟫	🟩	🟧	🟩	🟢	🟧	2.8
3		Crop protection[m]	🟫	🟫	🟨	🟢	🟢	🟧	🟩	🟢	🟩	3.2
4		Energy use in operations[n]	🟫	🟫	🟫	🟩	🟨	🟧	🟢	🟢	🟫	2.4
5	Storage (cooling, sprout control)		🟫	🟫	🟫	🟢	🟩	🟫	🟢	🟢	🟧	2.6
6	Transport[o]		🟫	🟫	🟫	🟩	🟢	🟧	🟩	🟨	🟨	2.8
7	Washing[p]		🟫	🟨	🟢	🟫	🟨	🟧	🟫	🟫	🟫	1.9
8	Heating[q]		🟫	🟫	🟫	🟩	🟨	🟧	🟫	🟫	🟧	1.9
9	Cooling, freezing		🟫	🟫	🟫	🟧	🟩	🟫	🟫	🟫	🟫	1.6
10	Mechanical operations[r]		🟫	🟫	🟫	🟧	🟢	🟧	🟫	🟫	🟫	1.6
Average			1.3	1.4	1.9	3.3	4.1	2.0	3.0	2.7	1.9	2.4

m Includes energy embedded in its production

n Traction only, irrigation apart in the first row

o Transport of tubers to factory, of products from factory to shops and from shops to users

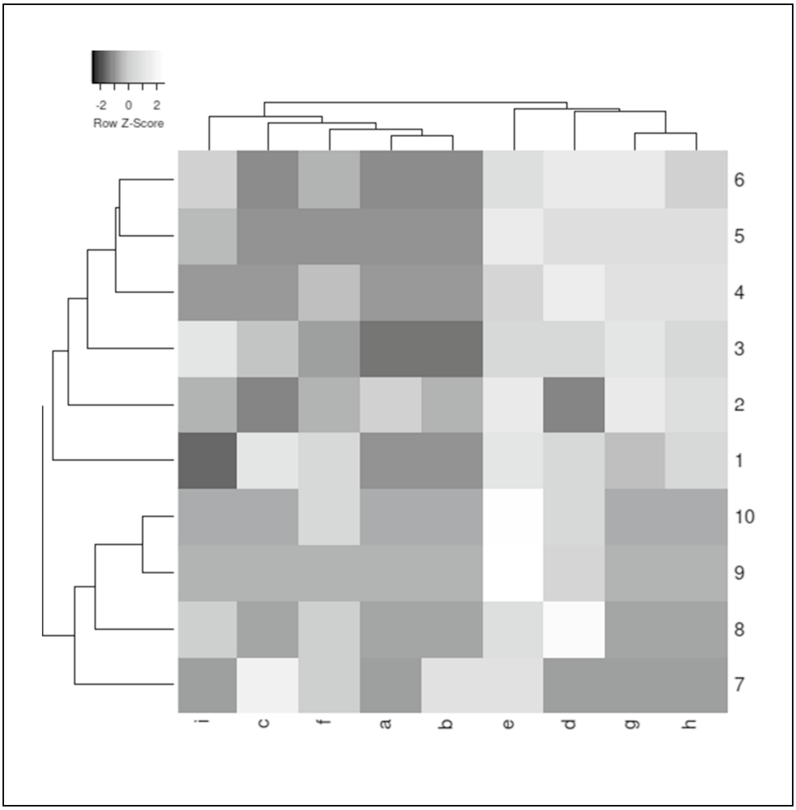
p Washing of tubers, of peeled tubers (after washing) and of starch

q Steam peeling, pre-heating, blanching, frying, drying (drum, flash), baking

r Abrasive peeling, sorting, grading, cutting, grinding, conveying affect energy from fuel and electricity, and only a few exert an influence on soil health, fertility and water need.

Irrigation receives the highest average value of all attributes (3.3) as almost all, human health exempted, habitat-affecting attributes apply to a large (energy and water need) or to a lesser degree (soil health and fertility). Crop protection also has a high average score with only low values for soil. The relatively confined and contained factory operations all receive low scores of 1.9 on average to 1.6 as they pose few threats to the habitat. Average values of attributes over all classes of operations are the lowest for soil fertility and health (1.3 and 1.4) as they affect few classes, and highest for the use of electricity as in all operations to a greater or lesser degree, electricity is involved. The attributes are not weighed so possibly, the fuel score of 3.3 for diesel for traction on farms and transport and frying in factories is impacting habitat through CO_2 and particulate matter more than electricity, especially when partly derived from renewable resources. This is open for debate.

Table 18 Dendrogram of operations (1-10, see Table 17) and their negative impact on the habitat expressed by their attibutes (a-i, see Table 17)



Clustering of Impact on Habitat

The factory operations are in one cluster and transport and farm operations in another (Table 18). Cooling and mechanical operations in factories have much in common as they both use electricity and fertilisation and driving machines as both are consuming much energy. Storage and transport, albeit at a large distance, have several attributes in common concerning toxic effects on the environment and humans.

The attributes show two distinct clusters with on the right the close twins ecotoxicity and biodiversity with energy needs at quite some distance. This is indicative that CO_2 associated with energy production is linked to the ecosystem. The larger cluster on the right holds the doubles soil fertility and health with decarbonisation opportunities, water need and risks for human health at increasing distances.

Quantification of Losses and Wastes

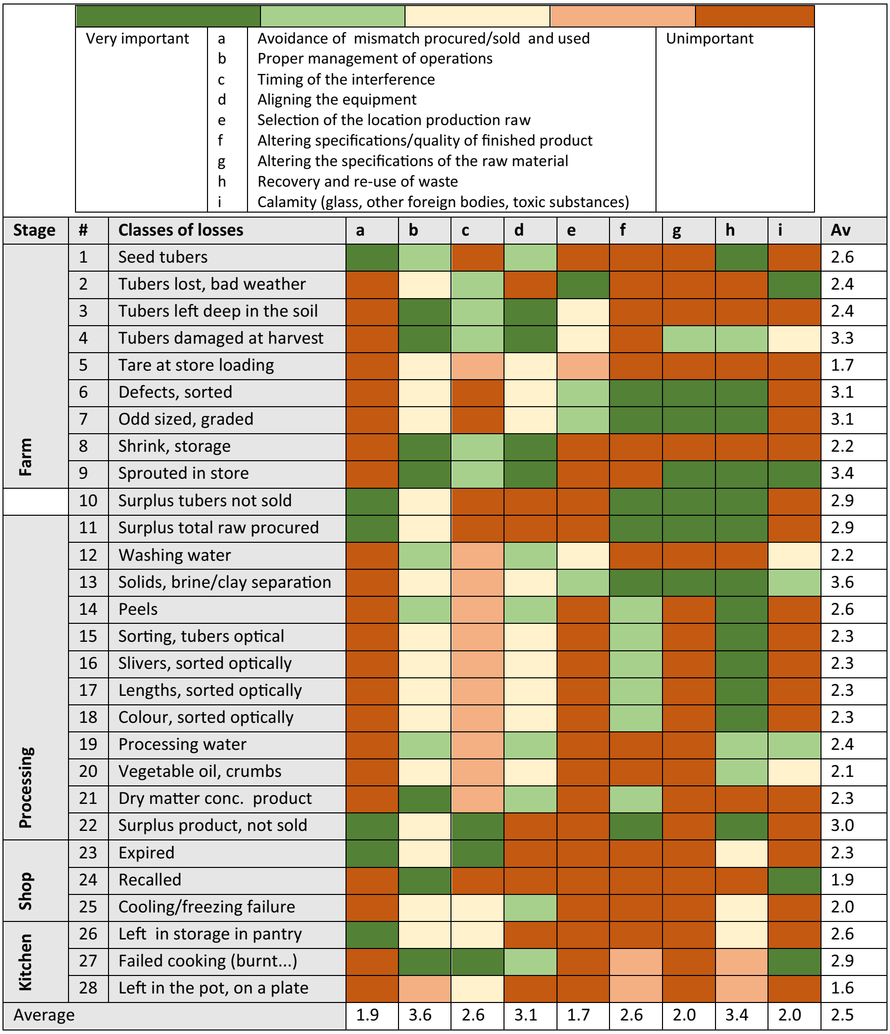
Several opportunities exist (Table 19) to diminish losses in the production of tubers, products and dishes. Buying and selling the appropriate quantity of seed tubers, ware tubers and products by growers, processors, shops and cooks reduce losses as mismatches here lead to depreciation and alternative use as a lower value side stream. Managing operations such as dose and amounts influence wastes as well as their proper timing. Adequate aligning of machinery, such as the scissors of diggers and optical sorters, avoids losses. Where there is a threat of losses occurring due to the environment or specifications, strategic decision assists such as looking for sites with fewer risks of losing crops due to adverse weather, or altering the specifications of raw as to meet the demand, similarly to those of the finished products. In years with low yields, smaller tubers and shorter French fries have to be accepted to reduce losses and meet demands. Recovery of otherwise wasted material to be used as a side flow is valid for surpluses and sorted and graded material as feed or raw material of flakes. Some calamities such as floods, glass in stores or noxious chemicals lead to losses or recalls but adequate prevention offers opportunities to reduce these.

The average values of the scores of the attributes per class are shown in the rows of the heatmap in Table 19. Losses at the table seem hardest to avoid by the opportunities enumerated in Table 19 with an average of 1.6 only. This is similar to tare such as adhering soil and stones where only aligning the harvester has some influence. Harvest damage, sprouting and low solids as becomes apparent in the separation of tubers in a brine solution, offer the most chances through interferences.

The average values of the scores per attribute over all classes are shown at the bottom of the columns. Better management in general and re-use are the best means of interference with an average of 3.6 and 3.4, with site selection offering the slightest chance (1.7).

Cluster analysis demonstrates three clusters of classes, one centred around the crop, one around recovery and dry matter and one focusing on the concentration of

Table 19 Heatmap of 28 classes of losses with 9 attributes: the opportunities to reduce wastes and losses of material



🟩 🟢 🟨 🟧 🟫

Very important … Unimportant

- a Avoidance of mismatch procured/sold and used
- b Proper management of operations
- c Timing of the interference
- d Aligning the equipment
- e Selection of the location production raw
- f Altering specifications/quality of finished product
- g Altering the specifications of the raw material
- h Recovery and re-use of waste
- i Calamity (glass, other foreign bodies, toxic substances)

Stage	#	Classes of losses	a	b	c	d	e	f	g	h	i	Av
Farm	1	Seed tubers	🟩	🟢	🟫	🟢	🟫	🟫	🟫	🟩	🟫	2.6
	2	Tubers lost, bad weather	🟫	🟨	🟢	🟫	🟩	🟫	🟫	🟫	🟩	2.4
	3	Tubers left deep in the soil	🟫	🟩	🟢	🟩	🟨	🟫	🟫	🟫	🟫	2.4
	4	Tubers damaged at harvest	🟫	🟩	🟢	🟩	🟨	🟫	🟢	🟢	🟨	3.3
	5	Tare at store loading	🟫	🟨	🟧	🟨	🟧	🟫	🟫	🟫	🟫	1.7
	6	Defects, sorted	🟫	🟨	🟫	🟨	🟢	🟩	🟩	🟩	🟫	3.1
	7	Odd sized, graded	🟫	🟨	🟫	🟨	🟢	🟩	🟩	🟩	🟫	3.1
	8	Shrink, storage	🟫	🟩	🟢	🟩	🟫	🟫	🟫	🟫	🟫	2.2
	9	Sprouted in store	🟫	🟩	🟢	🟩	🟫	🟫	🟩	🟩	🟩	3.4
	10	Surplus tubers not sold	🟩	🟨	🟫	🟫	🟫	🟩	🟩	🟩	🟫	2.9
Processing	11	Surplus total raw procured	🟩	🟨	🟫	🟫	🟫	🟩	🟩	🟩	🟫	2.9
	12	Washing water	🟫	🟢	🟧	🟢	🟨	🟫	🟫	🟫	🟨	2.2
	13	Solids, brine/clay separation	🟫	🟨	🟧	🟨	🟢	🟩	🟩	🟩	🟢	3.6
	14	Peels	🟫	🟢	🟧	🟢	🟫	🟢	🟫	🟩	🟫	2.6
	15	Sorting, tubers optical	🟫	🟨	🟧	🟨	🟫	🟢	🟫	🟩	🟫	2.3
	16	Slivers, sorted optically	🟫	🟨	🟧	🟨	🟫	🟢	🟫	🟩	🟫	2.3
	17	Lengths, sorted optically	🟫	🟨	🟧	🟨	🟫	🟢	🟫	🟩	🟫	2.3
	18	Colour, sorted optically	🟫	🟨	🟧	🟨	🟫	🟢	🟫	🟩	🟫	2.3
	19	Processing water	🟫	🟢	🟧	🟢	🟫	🟫	🟫	🟢	🟢	2.4
	20	Vegetable oil, crumbs	🟫	🟨	🟧	🟨	🟫	🟫	🟫	🟢	🟨	2.1
	21	Dry matter conc. product	🟫	🟩	🟧	🟢	🟫	🟢	🟫	🟫	🟫	2.3
	22	Surplus product, not sold	🟩	🟨	🟩	🟫	🟫	🟩	🟫	🟩	🟫	3.0
Shop	23	Expired	🟩	🟨	🟩	🟫	🟫	🟫	🟫	🟨	🟫	2.3
	24	Recalled	🟫	🟩	🟫	🟫	🟫	🟫	🟫	🟫	🟩	1.9
	25	Cooling/freezing failure	🟫	🟨	🟨	🟢	🟫	🟫	🟫	🟨	🟫	2.0
Kitchen	26	Left in storage in pantry	🟩	🟨	🟨	🟫	🟫	🟫	🟫	🟨	🟫	2.6
	27	Failed cooking (burnt...)	🟫	🟩	🟩	🟢	🟫	🟧	🟫	🟧	🟩	2.9
	28	Left in the pot, on a plate	🟫	🟧	🟨	🟫	🟫	🟧	🟫	🟧	🟫	1.6
Average			1.9	3.6	2.6	3.1	1.7	2.6	2.0	3.4	2.0	2.5

components. Of the attributes, processing stands alone and variety and environment are closely related twins exerting similarly affecting classes and so are seed and crop protection, crop duration and yield.

Deliberations and Conclusions

This survey with a focus on production aspects of the umbrella domain "On Processing Potato" applied the Four-Tier Analysis starting with formulating and delimiting each of the domains: supply chain, performance of farms and factories and

Table 20 Overview of the four domains figuring in this survey

Domain	Classes	No	Example of class	Attributes	No	Example of attribute
Supply chain	Actors	9	Cooks	Subjects actors find important	14	Product price
Field and Factory	Performances	19	Yield	Yield influencing factor	11	Variety
Resource use	Operations	10	Transport	Affecting habitat	9	Eco-toxicity
Losses	Events	28	Sorting	Avoidance of losses	9	Proper timing
Total		66			43	

losses. In each domain, classes were identified and descriptors assigned in the process of domain condensation. The four heatmaps were quantified, and classes and attributes clustered. Table 20 gives an overview of these domains where in total 66 distinct classes were provided with in total 43 attributes allocated to relevant classes and awarded a score between 1 and 5 according to the degree they apply to a class. Losses due to bad weather can be avoided by site selection (dark green, a score of 5) but not by planting other seed tubers (dark red, a score of 1); sprouting is avoided by proper store management (5) not by altering the specifications of the finished products. The resulting heatmaps allow a quick overview of the relevance of classes with only a few actors interested in the availability of seed (average score of 2.8) but most are interested in the storability of the material they take care of. Yield delivered to factories is affected by most cropping practices (4.3) but the vitamin concentration of tubers hardly (1.7). Hierarchical clustering was revealed where classes or attributes are similar so need not be separated when dealt with. Examples are cooling and mechanical operations, both depending on electricity so with similar decarbonisation options. Similarly, the close attribute twins ecotoxicity and biodiversity merit a joint approach as becomes apparent from the dendrogram and where the heatmap shows the opportunities: reduction of transport.

The research questions proved to be relevant and were adequately addressed by the analysis. Here follow some conclusions per question.

Imaging Supply

Breeders interact strongly with processors because variety and environment exert the strongest influence on tuber yield and processing quality. In some instances, large processors have their own breeding department or own a breeding company. At an early stage, well before a variety is named, factories do proof runs with advanced material to assess the processing quality for the production of chips, flour, French fries and more. Although the quality of the product is visible in the finished products, flesh colour for instance, the breeder does not have the strongest say so. Of all the actors, the breeder only exchanges material with the seed growers and exchanges information with them and with the processors. The latter are most central in the supply chain and send information upstream and downstream and in almost all attributes of the classes of actors. Customers of processors and shops are not always cooks, as outlets such as restaurants, institutions and caterers have buyers of provisions they need. Eaters, cooks and buyers at the upper end of the chain have great interest in quality and use of old and new products whereas breeders and growers at the opposite end hardly show interest as they cannot influence this. The clustering shows this dichotomy with actors dealing with raw material and those processing and moving it upstream.

Efficiencies on Farms and in Factories

Tuber yield and quality depend on four major factors (G, E, M, S): the planted seed material (variety, seed age, size and health), where and when it is planted and managed by the grower. Society preferences and legislation impose further requirements on products and how they are brought about. These factors also largely determine the efficiency of resource use expressed as land use efficiency (yield) in t/ha, water use in g/l and seed use expressed a gram of tuber yield per gram seed tuber planted to name a few. The typical values given — 45, 6 and 20 — vary much reliant on the four factors and naturally fluctuate from 10 to 80, from 3 to 10 and from 10 to 30, respectively. Higher temperatures and an increase in the CO_2 concentration of the ambient air also impact yield especially potentially positively in temperate climates. G, E and M also influence the concentration of tuber components and the aptness for processing into classes of starch, chips, fried and chilled products expressed as recovery, the proportion of finished product extracted from the harvested tubers. Recovery follows from handling, storing and processing (H, S, P). The G, E, M, H, S and P aspects are made attributes of the classes of farm and factory performance indicators that very much apply to yields of tubers, chips and French fries and hardly to concentrations of constituents. Especially variety, environment (twins at a short distance in the cluster hierarchy) and processing impact classes most.

Resource Use in Factories

Energy in factories is from electricity and fuel (gas, diesel, coal), the latter partly used for frying and partly transferred to steam and applied in other processes such as peeling, blanching and drum drying. Electricity is for the pulse electric field, conveying, drying and cooling. Water is mainly used for washing fresh and peeled products, conveying agent through pipes and some for steam production. Different scientific literature sources produced diverse data on energy and water costs of production. Early sources compared factory product output with its energy and water input over a fixed period; others went into more detail per process and either or not take re-use of hot air from cooling or blanching to preheat tubers or intermediate products into account. Decarbonisation, mainly by electrification which gives opportunities to apply electricity from renewable resources, draws special attention with some companies declaring to become fully independent of fossil fuels in the future. Losses on farms follow from defects, grading and shrinkage in stores to name a few and from peels, slivers and starch at processing and thrown away in kitchens. Operations on farms (fertiliser use), in transport (diesel), cooling (electricity), factories (wastewater) and oil and energy use in kitchens involve not only loss but also negatively impact the environment and human health. Losses and wastes are partly avoidable through technology (genetics, adapting to climate change planning supply, through organisation (contracts, subsidies, legislation) and social behaviour). Quantification of the attributes avoidance of 28 classes of losses from planting to plate, yielded a heatmap showing that mismatch between supply and demand applied to few losses only and aligning equipment and aiming at high recovery touches many losses. Shops have the fewest possibilities to avoid losses because losses there are scarce, expired dates mainly. Sorting and grading are major operations where material is discarded and where only altering criteria, leniency, offers solace.

Losses on Fields and in Factories

Yields of fields are expressed as tonnes of tubers per hectare and in factories as kilograms of finished product per tonne of raw material. Yields are achieved at the expense of resources and inputs with an efficiency determined by unavoidable losses in fields and factories, by intended losses, by avoidable (to a certain degree) losses and wastes of resources and inputs. Intended losses are skin at peeling and water in the tubers at drying and frying. Avoidable losses, albeit not fully, are tubers left in the soil, rejection due to low solids and not emptying the plate. Partly avoidable wastes are water and nitrogen fertiliser in growing tubers, water and heat in processing and fruitless efforts in the kitchen. The most significant losses of tubers occur with sorting by eye, optics and brine of tubers and optical sorting of (semi) finished products. The cause is not sorting but lies in earlier avoidable losses.

Declarations

Conflict of Interest P. C. Struik is the editor-in-chief of Potato Research.

References

ADHB (2021) Potato Variety Database. https://varieties.ahdb.org.uk/varieties. Accessed on 11 April 2022

Aramyan L, Valeva N (2016) The Netherlands – country report on national food waste policy. pp 17. https://www.eu-fusions.org/phocadownload/country-report/NETHERLANDS%2023.02.16.pdf

Bahadirov G, SultanovUmarov B, Bakhadirov K (2020) Advanced machine for sorting potatoes tubers. IOP Conf Ser: Mater Sci Eng 883:012132. https://doi.org/10.1088/1757-899X/883/1/012132

Baltussen WHM, Dolman MA, Hoste R, Janssens SRM, Reijs JW, Smit AB (2016) Grondstofefficiëntie in de zuivel-, varkensvlees-, aardappel- en suikerketen. Wageningen University and Research centre LEI Nota 2016–013:86

Beretta C, Stoessel F, Baier U, Hellweg S (2013) Quantifying food losses and the potential for reduction in Switzerland. Waste Manage 33:764–773

Bethke PC, Jansky SH (2008) The effects of boiling and leaching on the content of potassium and other minerals in potatoes. J Food Sci 73:80–85

Betz A, Buchli J, Göbel C, Müller M (2015) Food waste in the Swiss food service industry – magnitude and potential for reduction. Waste Manage 35:218–226

Brown CR (2005) Antioxidants in Potato. Am J Potato Res 82:163–172

Caldeira C, De Laurentiis V, Corrado S, van Holsteijn F, Sala S (2018) Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour Conserv Recycl 149:479–488

Camire ME, Kubow S, Donnelly DJ (2009) Potatoes and Human Health. Crit Rev Food Sci Nutr 49:823–840

Canali M, Östergren K, Amani P, Aramyan L, Sijtsema S, Korhonen O, Silvennoinen K, Moates G, Waldron K, O'Connor C (2014) Drivers of current food waste generation, threats of future increase and opportunities for reduction. 8 | FUSIONS Reducing food waste through social innovation, ISBN: 978–94–6257–354–3, 188 pp

Devaux A, Goffart J-P, Kromann P, Andrade-Piedra J, Polar V, Hareau G (2021) The potato of the future: opportunities and challenges in sustainable agri-food systems. Potato Res 64:681–720

EFSA (2022) https://www.foodsafetynews.com/2020/08/efsa-assesses-health-risk-of-compound-in-potatoes/. Accessed on 19 June 2022

Eltawil M, Samuel D, Singhal O (2006) potato storage technology and store design aspects. Agricultural Engineering International: the CIGR Ejournal. Invited Overview No. 11. Vol. VIII, 12 pp

Emragi E, Sathuvalli V, Jayanty SS (2021) The impact of ventilation conditions on the quality of Rio Grande Russet tubers during long-term cold storage. J Agric Food Res 3 100095:8

FAO (2021) 2http://www.fao.org/prices/en/. Accessed on April 11 2022

Foster C, Green K, Bleda M, Dewick P, Evans B, Flynn A, Millan J (2006) Environmental impacts of food production and consumption a report to the Department for Environment, Food and Rural Affairs. Manchester business school DEFRA London. 197

Franke AC, Haverkort AJ, Steyn JM (2013) Climate change and potato production in contrasting South African agro-ecosystems 2. Assessing risks and opportunities of adaptation strategies. Potato Res 56:1–66

Gaisma (2021) https://www.gaisma.com/en/location/pocatello-idaho.html. Accessed on 11 April 2022

Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R, Meybeck A (2011) Global food losses and food waste. Extent, causes and prevention. Food and Agriculture Organization of the United Nations, Rome, p 29

Halseth D (2015) Chip variety trials. USPB/SFA. https://www.canr.msu.edu/potatooutreach/research/2015%20uspb-sfa%20chip%20variety%20trials%20and%20early%20chipping%20report.pdf. Accessed on 11 April 2022

Han JS, Kozukue N, Young K-S, Lee K-R, Friedman M (2004) Distribution of ascorbic acid in potato tubers and in home-processed and commercial potato foods. J Agric Food Chem 52:6516–6521

Haruko Okamoto H, Ducreux LJM, Allwood JW, Hedley PE, Wright A, Gururajan V, Terry MJ, Taylor MA (2020) Light regulation of chlorophyll and glycoalkaloid biosynthesis during tuber greening of potato S. tuberosum. Front Plant Sci 11:1–19. https://doi.org/10.3389/fpls.2020.00753

Haverkort AJ (1990) Ecology of potato cropping systems in relation to latitude and altitude. Agric Syst 32:251–272

Haverkort AJ, Hillier JG (2011) Cool farm tool – potato: model description and performance of four production systems. Potato Res 54:355–369

Haverkort AJ, Struik PC (2015) Yield levels of potato crops: recent achievements and future prospects. Field Crops Res 182:76–85

Haverkort AJ, Franke AC, Engelbrecht FA, Steyn JM (2013) Climate change and potato production in contrasting South African agro-ecosystems 1. Effects on Land and Water Use Efficiencies. Potato Res 56:31–50

Haverkort AJ, Franke AC, Steyn JM, Pronk AA, Caldiz DO, Kooman PL (2015) A robust potato model: LINTUL-POTATO-DSS. Potato Res 58:313–327

Haverkort AJ (2018) Potato Handbook, crop of the future. Potato World, pp 600

Haverkort AJ, Linnemann AR, Struik PC, Wiskerke JSC (2022a) On processing potato. 1. Survey of the ontology, history and participating actors. Potato Res. https://doi.org/10.1007/s11540-022-09562-z

Haverkort AJ, Linnemann AR, Struik PC, Wiskerke JSC (2022b) On processing potato, 2. Survey of processes and operations in manufacturing products. Potato Res https://doi.org/10.1007/s11540-022-09563-y

Haverkort AJ, Linnemann AR, Struik PC, Wiskerke JSC (2022c) On processing potato, 4. Survey of the nutritional and sensory value of products and dishes. Potato Res. https://doi.org/10.1007/s11540-022-09568-7

IPCC (2021) https://www.ipcc.ch/srccl/download/. Accessed on 11 April 2022

Jaggard KW, Qi A, Ober AA (2010) Possible changes to crop yield by 2050. Philos Trans Roy Soc Bot 365:2835–2851

Johns T, Alonso JG (1990) Glycoalkaloid change during the domestication of the potato, Solanum Section Petota. Euphytica 50:203–210

Kantor LS, Lipton K, Manchester A, Oliveira V (1997) Estimating and addressing America's food losses. Food Review 4:12

Kiil K, Hvolby H, Trienekens J, Behdani B, Strandhagen JO (2019) From information sharing to information utilization in food supply chains. Int J Inf Syst Supply Chain Manag 12:85–109

Kooman PL, Haverkort AJ (1994) Modelling development and growth of the potato crop influenced by temperature and daylength: LINTUL-POTATO. In: Haverkort AJ, MacKerron DKL (eds) Ecology and modeling of potato crops under conditions limiting growth. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 41–60

Kranert M, Hafner G, Barabosz J, Schuller H (2012) Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland. https://www.nachhaltigkeit.steiermark.at/cms/dokumente/12600659_139338025/395cf635/1_0202%20BRD%20Studie_Lebensmittelabfaelle Kurzfassung.pdf, 42 pp. Accessed on April 11 2022.

Kropff MJ, Haverkort AJ, Aggarwal PK, Kooman PL (1995) Using systems approaches to design and evaluate ideotypes for specific environments. In: Bouma J et al (eds) Eco-regional approaches for sustainable land use and food production. Wageningen Academic Publishers, Wageningen, The Netherlands, pp 417–435

Machida-Hirano R (2015) Diversity of potato genetic resources. Breed Sci 65:26–40

Masanet E, Worrell E, Graus W, Galitsky C (2008) Energy efficiency improvement and cost saving opportunities for the fruit and vegetable processing industry: an ENERGY STAR guide for energy and plant managers. Lawrence Berkeley National Laboratory, pp 172

Mattson B, Wallen E (2003) Environmental LCA of organic potatoes. ISHS. 26the International Horticultural Congress. Acta Hort 619:427–435

Mazza G, Siemens AJ (1990) Carbon dioxide concentration in commercial potato storages and its effect on quality of tubers for processing. Am Potato J 67:121–134

Mouron P, Willersinn C, Möbius S, Lansche J (2016) Environmental profile of the swiss supply chain for french fries: effects of food loss reduction, loss treatments and process modifications. Sustainability 8:1214–1234

NASA (2021) https://power.larc.nasa.gov/. Accessed on 11 April 2022

Olsen P, Aschan M (2010) Reference method for analyzing material flow, information flow and information loss in food supply chains. Trends Food Sci Technol 21:313–320

Paul V, Ezekiel R, Pandey R (2016) Sprout suppression on potato: need to look beyond CIPC for more effective and safer alternatives. J Food Sci Technol 53:1–18

Pedreschi F, Mery D, Marique T (2016) Chapter 15 - grading of potatoes. Computer vision technology for food quality evaluation, 2nd edn. pp 369–382

Rastovski A, van Es A (1985) Post-harvest behaviour, store design, storage practice, handling. Storage of potatoes. Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands, 462

Rijksdienst voor Ondernemend Nederland (2016) MJA Sectorrapport 2015: Aardappelverwerkende s11540–013–9229-x industrie. Utrecht industrie, Utrecht, The Netherlands, p 10

Seal CJ, de Mul A, Eisenbrand G, Haverkort AJ, Franke K, Lalljie SPD, Mykkanen H, Wilms L (2008) Risk-benefit considerations of mitigation measures on acrylamide content of foods - a case study on potatoes, cereals and coffee. British Journal of Nutrition 99 (SUPPL. 2):S1-S46

Sengul M, Keles F, Keles MS (2004) The effect of storage conditions (temperature, light, time) and variety on the glycoalkaloid content of potato tubers and sprouts. Food Control 15:281–286

Somsen D (2004) Production yield analysis in food processing: applications in the French fries and the poultry-processing industries. Wageningen University and Research, Wageningen, The Netherlands, PhD Thesis, p 240. http://edepot.wur.nl/121537

USFDA (2021) https://www.cfsanappsexternal.fda.gov/scripts/Plantox/Detail.CFM?ID=6537. Accessed on 11 April 2022

Uyen N, Vander Zaag P (2008) Potato production using tissue culture in Vietnam: the status after four years. Am Potato J 60:873–879

Van der Waals JE, Franke AC, Haverkort AJ, Krüger K, Steyn JM (2013) Climate change and production in contrasting South African agro-ecosystems 3. Effects on relative development rates of selected pests and pathogens. Potato Res 56:67–84. https://doi.org/10.1007/s11540-013-9231-3

Van Loon J (2019) Door eendrachtige samenwerking – De geschiedenis van de aardappelveredeling in Nederland, van hobby tot industrie. 1888–2018, 407 pp

Walker C, Beretta C, Sanjuán N, Hellweg S (2018) Calculating the energy and water use in food processing and assessing the resulting impacts. Int J Life Cycle Assess 23:824–839

Wang-Pruski G, Nowak J (2004) Potato after-cooking darkening. Am J Potato Res 81:7–16

West KJ, de Jonge JJ, van Hout M (2020) Decarbonisation options for the Dutch potato processing industry. © PBL Netherlands Environmental Assessment Agency, PBL publication number: 3658. Publication number: TNO 2020 P11023, 46

Willersinn C, Mack G, Mouron P, Keiser A, Siegrist M (2015) Quantity and quality of food losses along the Swiss potato supply chain: Stepwise investigation and the influence of quality standards on losses. Waste Manage 46:120–132

Williams AG, Audsley E, Sandars DL (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main Report DEFRA Research Project IS0205. Bedfort Granfield University and DEFRA, p 97

WRAP (2012) https://wrap.org.uk/resources/case-study/reducing-supply-chain-and-consumer-potato-waste-case-study. Accessed on 11 April 2022

Wu H, Jouhara H, Tassou S, Karayiannis T (2010) Modelling of energy flows in potato crisp frying processes. Appl Energy 89:81–88

Yagiz AK, Cakici M, Aydogan N, Omezli S, Yerlikaya BA, Ayten S, Maqbool A, Haverkort AJ (2020) Exploration of climate change effects on shifting potato seasons, yields and water use employing NASA and National Long-Term Weather Data. Potato Res 63:565–577