Master's Thesis

Master Sustainable Business & Innovation

Peeling back the layers

Uncovering the potential of Potato Peels

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Abstract

This thesis investigates the potential for enhancing the uptake of high-nutritional-value substances from potato peels to improve resource efficiency in the Dutch potato processing industry. It explores the multifaceted aspects of potato peel valorisation by analysing current utilization practices, technological advancements, and stakeholder influences within a framework that supports sustainable agricultural practices.

The study begins by contextualizing the significance of potato peels as a byproduct in the Netherlands, outlining the economic and environmental incentives for valorising this underutilized resource. The main research question explores how the recovery and utilization of valuable substances from potato peels can be increased.

A comprehensive review of existing literature establishes a theoretical foundation, identifying the nutritional potentials of potato peels, their current applications, and the technological barriers to their valorisation. Semi-structured interviews with relevant stakeholders from the industry provide the research with real-world examples and insights.

Results reveal that while potato peels are primarily used for biogas production and animal feed, there are significant opportunities for higher-value applications. Technological innovations in extraction and processing methods are critical to overcoming current limitations. The Stakeholder analysis underscores the need for collaborative approaches involving government incentives, research advancements, and industry participation to foster a favourable environment for innovation.

The discussion integrates these findings, highlighting the synergy between technological feasibility, economic viability, and regulatory support in optimizing the valorisation process. It also addresses the challenges and opportunities identified through stakeholder insights, suggesting strategic directions for policy and practice. It is however recommended that further research in the economic feasibility of such valorisation processes is needed in order to scale up to full commercialization.

The thesis concludes that increasing the uptake of high-nutritional-value substances from potato peels is not only technically feasible but also environmentally beneficial. It advocates for a shift in perception from viewing potato peels as waste to recognizing them as valuable resources, calling for systemic change towards sustainability in the agrifood sector. This thesis encourages continued exploration, innovation, and collaboration to fully realize the benefits of byproduct valorisation in the Netherlands and beyond.

Table of contents

1. Introduction

1.1 problem statement

Our global population is growing, and with it, our global food consumption and waste production (Sarihan, 2023). Consequences of this growth are escalating environmental impact and the urgency to foster sustainable production and consumption practices. Therefore, more attention has gradually shifted towards the concept of the Circular economy (Geissdoerfer et al., 2017). As circular concepts are becoming more common, there is a developing transformation on how organizations perceive and utilize resources. Resource efficiency is often seen as a key principle towards more circular supply chains (Wilts & O'Brien, 2019) and a vital strategy to improve one's resource efficiency is the optimization of waste flow management. Strategies to optimize waste flows offer a pragmatic solution to the increasing amount of global waste produced. Reducing and reusing waste will not only reduce the overall quantity, but it can potentially also create opportunities to turn byproducts, that are currently regarded as waste, into resources. (Kurdve et al., 2015; Das et al., 2019; Chen et al., 2020).

A particular byproduct that holds such a potential can be found in the processing of potatoes. The potato is the fourth most imported agricultural product worldwide (Dreyer, 2017), and the processing of potatoes produces various waste flows which can cause economic and environmental problems if not properly utilized (Pal, 2018). The potato peel is one of those flows and represents up to 10% of total waste flow obtained during the processing phase of potatoes, making it the largest waste stream (Janssens & Smith, 2016; Rodríguez-Martínez et al., 2021). At the moment, potato peels are mainly used for animal feed or biogas production (Pal, 2018; Almeida et al., 2023) and can cause environmental damage if not utilized due to decomposition (Gebrechristos & Chen, 2018). Even though the peel currently has a destination, the interest in the potato peel has grown in recent publications (Santos et al., 2016) specifically because of the fact that valuable nutrients and compounds can possibly be extracted from this potato byproduct (Sepelev & Galoburda, 2015; Gebrechristos & Chen, 2018). It is known that these peels are a great source of starch, but potato peels also contain phenolic compounds (Akyol et al., 2016), protein (Taskila et al., 2018) and other nutrients which can be won through various extraction methods.

The interest in these nutrients and compounds comes from the increasing global demand for plant-based food products. In the past decade, the global plant-based food market has grown significantly and is expected to follow this trend for the coming years (FMI, 2023; Williams, 2023). Key factors driving this trend are: growing environmental, human-health and animal-welfare concerns amongst consumers (He et al., 2020; Aschemann-Witzel et al., 2020; Alcorta et al., 2021; Hargreaves et al., 2021). Currently roughly 18% of the world's population is strictly vegetarian (Phoenix, 2024), and growing rates have been reported in countries such as the UK, the US, and several European countries (Buchholz, 2022). Meat is a good source of protein, but as consumers are changing their diets, there is a growing demand for plant-based protein (Kumar et al., 2016). The interest in phenolic compounds is also high as they could help to reduce mortality rates due to non-communicable diseases (NCDs) (Direito et al., 2021). NCDs, which are more prevalent in high-income countries, are now increasing in developing and poor countries due to changing environmental and behavioural factors (Lloyd-Sherlock et al., 2016 & WHO, 2023). The most prominent NCDs are cancer, cardiovascular disease, Chronic obstructive pulmonary diseases (COPD) and diabetes which are all linked to preventable risk factors related to lifestyles (Alwan & MacLean, 2009; Checkley et al., 2014). The intake of phenolic compounds can have a positive effect on the prevention of NCDs. A person having deficits in antioxidants, phenolics compounds act as antioxidants, can suffer from imbalanced oxidative stress, which on terms can lead to cancer, arteriosclerosis or degenerative aging processes due to the lack of neutralisation of free radicals (Aguilera et al., 2015; Ayoka et al., 2022; Echeverría & Valenzuela, 2022). As the health benefits of these compounds become more apparent, interest is growing in their usage in several industries (Albuquerque et al., 2021).

In conclusion, while potato peels are currently used for pig feed and biogas production, this approach overlooks their rich nutritional potential. These peels hold promise as a source for plant-based health supplements, and address the modern concept of viewing waste not merely as a byproduct but as a valuable resource. Therefore, countries such as the Netherlands that have a high potato yield, could potentially benefit from recovering high-value substances from potato peels.

1.2 Scientific background

Current academic research on potato peels has consistently highlighted that potato peels are a significant source of valuable nutrients. Among these studies Akyol et al. (2019) describe that potato peels are a great source of phenolic compounds as almost 50% of the phenolics are located in the peel. Their research mentions that the recovery of natural antioxidants in the peel may be economically attractive as they can be utilised as functional ingredients in food formulation. Sampaio et al. (2020) highlight the presence of phenolic compounds in the potato peel and, considering its nutritional value and chemical composition, could be of great interest for the food and pharmaceutical industry whilst simultaneously increasing the added value and minimize the environmental impact of the potato crop. Moreover, Almeida et al. (2023) indicate that the potato peel is rich in compounds like anthocyanins, glycoalkaloids, phenolic compounds, and flavonoids, which are all associated with health benefits as they protect body cells from oxidative processes. They highlight the value of potato peels, which are currently regarded as no-value byproducts, and the need to recover them.

Besides the nutritional value and extracting methods, Almeida et al. (2023) also discuss potential applications of using potato peels as a source of dietary fibre; in bakery production; as a source of natural antioxidants and in food coatings. They emphasise that the integration of multiple processes and the techno-economic analysis for managing potato peel is still scarce. Rodríguez-Martínez et al. (2021) also explain the high nutritional value of the potato peel and the potential environmental and economic challenges if the peels are not managed properly. They conclude that the potato peel can be used to recover bioactive compounds with high added-value polyphenols, glycoalkaloids, polysaccharides and thus not only mitigate environmental problems but can also enhance the profitability of the food industry. They conclude that in this potato peels could open future industrial applications that would allow the full use of this by-product.

Taskila et al. (2018) researched the potential of potato protein and concluded that potato peel waste (PPW), with minor supplementation, is a suitable raw material for the production of single cellular proteins (SCP). Joshi et al. (2020) also highlight the use of potato peels for the production of SCP, but also further elaborate on non-food applications for the potato peel such as a safe alternative of metallic nano-particles; for the production of enzymes which can be further used in textile; applications in the paper industry; as substrate for fermentation and lastly for the production of biofuel.

Despite this established nutritional value, there is a notable gap in research from a techno-economic perspective. The broader utilization of potato peels beyond animal feed and biogas production(Sampaio et al., 2020; Almeida et al., 2023), especially in terms of economic and technical feasibility, remain largely unexplored. This lack of comprehensive research presents an opportunity to truly define the potential of this potato byproduct. It is know by now that it is possible to extract this nutritional value from the peel but very few publications actually report on a successful deployment of this process, even though some studies already suggested such deployments. Sampaio et al. (2020) suggested that the food and drug industries may find a lot of potential for potato peels, and Rodríguez-Martínez et al. (2021) agreed and added that the potato peel may lead to new industrial uses that would make this byproduct entirely useful. Akyol et al. (2019) suggested that it might be profitable to recover the nutrients from the peel. Therefore, this thesis investigates the feasibility of extracting and using high-value nutrients from potato peels on a large scale in food processing considering economic, governance and technical factors. The latter will be reported according to the widely used Technology Readiness Level (TRL) scale, which is commonly referred to in the context of sustainable practices and innovations in the food sector (Van Cauwenbergh et al., 2022). The research focusses on the Netherlands, as it is the biggest exporter of potato's worldwide (OEC, 2022), with the final goal of improving the recovery and use of high-nutritional-value substances from potato peels. The main research question to address this concept is formulated as follows:

How can the uptake of high-nutritional-value substances from potato peels be increased to enhance resource efficiency in the Netherlands?

The following sub-questions have been formulated to guide the research:

1) *How are potato peels currently utilized in food processing and other industries?*
2) *What agency and influence can the stakeholders in the Dutch potato by-product valorisation ecosystem have?*
3) *What is the techno-economic feasibility, including Technology Readiness Levels, of implementing the recovery of high-nutritional-value substances from potato peels?*

1.3 Scientific relevance

There is already substantial academic literature on the potato peel and its beneficial attributes from a natural scientific point of view. This research will focus on addressing the barriers to development within the Dutch market, which produced roughly 7 million tonnes of potatoes in the year 2022, and is currently ranked 9th in production on a global scale (PotatoPro, 2023). Furthermore, this thesis will delve into various factors that determine the success rate of a broader usage of potato peels in high-value applications. Techno-economic factors will be taken into account, which are currently hard to determine as most literature focussed on natural scientific perspectives. The results of this research might not only offer a pragmatic solution for utilizing potato peels, but could possibly also inspire to be applied to various other waste flows for different crops in the food processing sector.

1.4 Societal relevance

As the global population and levels of affluence in low-middle income countries continue to increase, so do global food consumption and food waste throughout the value chain. Within this trend, agricultural waste is estimated at roughly 998 million tonnes per year (Raut et al., 2023).

Big proportions of this waste currently end either disposed of to land or as animal feed, this also applies to the potato peel. Although animal feed is a route to dispose the peels, transporting the peels to landfill and incinerate or store the peels on the other hand, can cause environmental degradation (Rodríguez-Martínez et al., 2021). Similarly, using the peels as animal feed will be less necessary if livestock rates drop in the future, as a consequence of changing consumer behaviour towards lower meat consumption (Rust et al., 2020). Potato peel utilization is not only in line with the trend of offering a solution to global waste production, but it also holds health beneficial components that can be used to reduce risk of cancer, cardiovascular diseases, Chronic obstructive pulmonary disease or diabetes (Ayoka et al., 2022; Echeverría & Valenzuela, 2022), diseases that are still on the rise anno 2023 (WHO, 2023). If these various phytonutrients can be extracted and processed into food products or supplements, they could be of great added-value. The nutrients can either be used to cope with the increasing demand for plant-based foods due to changing consumer diets, or to alleviate the increasing mortality rate due to NCDs.

2. Theory

This chapter defines key concepts which will be implemented in this research. Each concept will briefly be explained and subsequently how they should be perceived in the context of the thesis.

2.1 Resource efficiency

Resource efficiency is an important aspect of modern sustainable practices, aiming to minimize material inputs, maximize economic outputs, and respect the limits of the environment (Van Ewijk, 2018). Resource efficiency in agriculture and food processing includes not only water and energy conservation, but also the optimal use of raw materials and byproducts (Jagtap et al., 2021). This approach not only promotes environmental sustainability, but it also increases economic viability by reducing waste and recovering value from residues and to facilitate innovation towards a circular economy (Flachenecker & Rentschler, 2018).

Van Hout et al. (2020) provide an overview of the Dutch potato industry covering various aspects of processing the potatoes from raw crop to final frozen products. Notably, every 2 tonnes of raw potatoes processed yields approximately 0.4 tonnes of potato peels, which comes down to a remarkable 20% of the initial raw product:

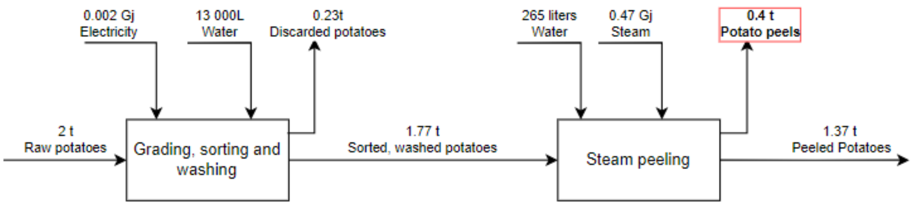

Figure 1 - flow diagram of 2 tons raw potatoes adapted from Van Hout et al. (2020)

Potato peels are currently often discarded or used for low-value applications such as animal feed, biogas or compost (Janssens & Smith 2016). While such practices help to reduce waste disposal, they do not fully realize the potential value of these byproducts. The lack of high-value utilization of potato peels represents a gap in achieving optimal resource efficiency in the potato processing industry.

The following biorefinery model of Rodríguez-Martínez et al. (2021) provides an example of what can be extracted from this significant 20% of total product input flux in the potato industry :

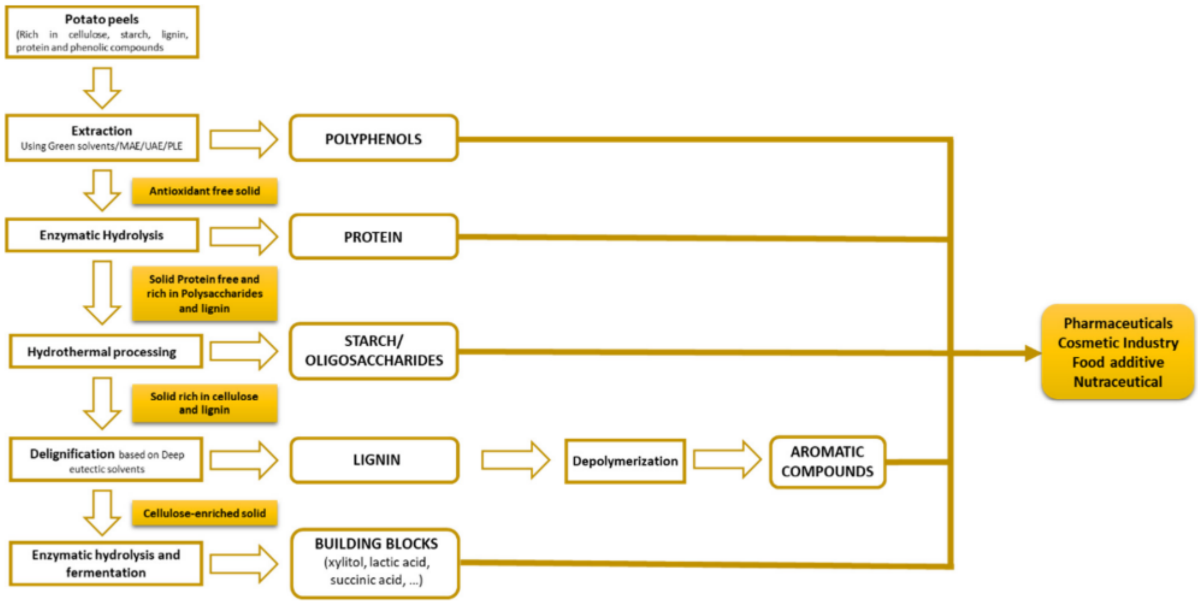

Figure 2 - Integrated biorefinery model for potato peel waste (Rodríguez-Martínez et al., 2021)

This figure shows that the polyphenols, protein, oligosaccharides, and lignin can be reused in different industries. Note that multiple substances can be extracted from the same potato peel mass, making it an valuable byproduct. The valorisation of potato peels demonstrates a shift toward more sustainable waste management, and aligns with larger environmental goals such as lowering greenhouse gas emissions and conserving resources (Gaudino et al., 2020). The next paragraph defines the different substances in the potato peel, and their possible effects or uses.

2.2 Potato peel added-value

The potato peel holds promising attributes to contribute towards addressing the growth in global waste generation whilst also providing high nutritional value. The potato peel accounts for 10 to 20%, depending on the processing method, of the total potato mass. The peel is currently regarded as zero-value waste (Abdelraof et al., 2019) and is often costly to dispose, creating negative value (Pal, 2018). These promising attributes makes the peel suitable for the production of biopolymers and high-value extracts (Muthurajan et al., 2021). Within the potato peel, the following phytonutrients can be found (Elkahoui et al., 2018; Sampaio et al., 2020; Rodríguez-Martínez et al., 2021):

1. Polysaccharides (starch and non-starch)
2. Glycoalkaloids
3. Protein
4. Fibre
5. Phenolic compounds
6. Traces of other minerals and compounds

It is important to note that the exact composition and quantities differ per potato and growing conditions, but one can assume that the above mentioned compounds can be found in the potato peel (Rodríguez-Martínez et al., 2021).

Polysaccharides, such as starch, are a good source of energy for the human body. The starch in a potato peel accounts for 40 to 50 percent of total dry weight (Sampaio et al., 2020), and can promote gut health and aid in blood sugar regulation (Keskin et al., 2021). Glycoalkaloids, despite being toxic when high concentrations are ingested, have anti-inflammatory and anti-cancer properties due to their bioactivity, and can be used for precursors in the treatment if certain skin diseases (Rodrigues-Martínez et al., 2021). Pectin is a non-starch polysaccharides, which is often used as a gelling agent, thickening agent and stabiliser in food products (Flutto, 2003). Gavahian et al. (2021) concluded in their research that the potato peel pulp, with the right extraction method, shows great efficiency for pectin extraction. Protein is a nutrient that is essential for the growth, repairing and maintenance of muscle tissue (Kreider & Campbell, 2009). The range of protein that is found in potato peels sits between 2 and 15 percent of total dry weight (Sampaio et al., 2020; Rodrigues-Martínez et al., 2021). Fibers help to regulate healthy cholesterol levels and while providing an overall feeling of fullness, they promote gut health which helps to create a stronger immune system (Keskin et al., 2021). Fibre is a main component of potato peel as it roughly accounts for 40 to 45 percent of total dry weight (Rodríguez-Martínez et al., 2021). Lastly, phenolic compounds are antioxidants that have various health benefits. The two most present phenolic compounds in potato peels are phenolic acids and flavonoids, which both limit the risk of non-communicable diseases linked to oxidative stress (Akyol et al., 2016).

2.3 Extraction methods

Until now, the properties of the potato peel and their purpose have been explained. In this chapter the extraction methods that can be used to recover these high-value substances are defined. Currently the most conventional method to extract bioactive compounds from potato peel is done with a Soxhlet or heat reflux (Jimenez-Champi et al., 2023). This method results in high extractions, but is not considered environmentally friendly as the solvents used are toxic (Jimenez-Champi et al., 2023). However, more innovative and sustainable extraction methods have been developed.

Ultrasound-assisted Extraction (UAE) uses ultrasound waves to break down plant cells, which allows for extraction of phenolic compounds, pectin, protein and amino acids. This method is considered more sustainable as no toxins are used, but it can potentially degrade some of the compounds (Rodríguez-Martínez et al., 2021). Microwave-Assisted Extraction (MAE), uses microwaves to heat up the plant material, in this case potato peels, to extract antioxidants and other beneficial compounds. It is faster than conventional heating and uses less solvent, however some delicate compounds might degrade and thus result in a lower extraction yield (Rodríguez-Martínez et al., 2021; Jimenez-Champi et al., 2023).

There are other alternatives such as Supercritical Fluid Extraction (SFE), Pressurized Liquid Extraction (PLE) and Solid-liquid Extraction (SLE), but these methods require either a higher energy input (Jimenez-Champi et al., 2023), complex and costly equipment (Akyol et al., 2016) or specific solvent requirements (Rodríguez-Martínez et al., 2021; Jimenez-Champi et al., 2023).

2.4 Technology Readiness Levels

The technology readiness levels (TRL) scale, previously alluded to in the introduction, was initially developed by the National Aeronautics and Space Administration and is currently used by the European Commission for assessing and classifying innovations and organising funding (Dahan, 2021). The framework measures the maturity level of technology and links it to one of the TRL. The scale ranges from level one, where the basic concept and principles are formulated, to level nine, where the technology is fully commercialized and has been proven in an operational environment (RVO, 2022):

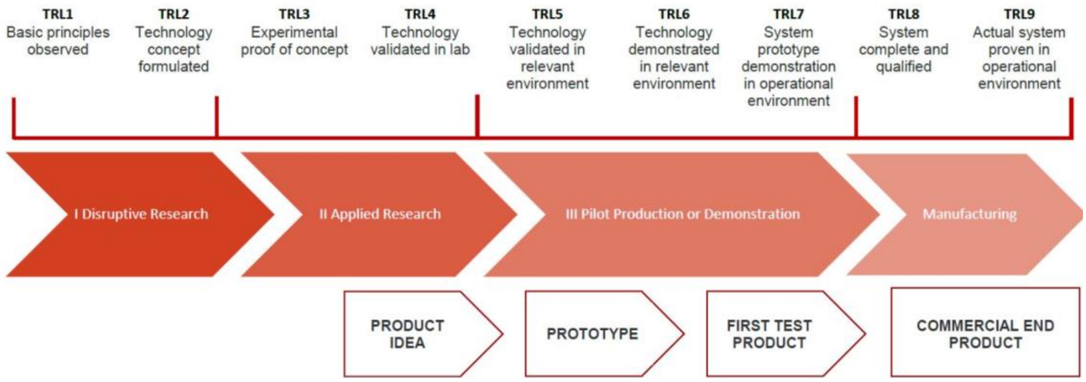

Figure 3 - Flow diagram of the TRL Framework (RedKnight Consultancy & Bid Writers, 2023)

A major benefit of using the TRL framework is that it is widely used, easily interpreted, and it helps to engage with important stakeholders (Olechowski et al., 2015). Within this research, the TRL framework plays an important part in assessing the stages of development of technologies used for the extraction of high-nutritional-value substances from potato peels and, therefore, their suitability to reach market maturity depending on socio-economic conditions.

3. Methodology

This chapter links the insight of the introductory chapters with the methodological concepts and steps used to answer the research questions. A brief description of the design, data gathering, operationalization, sampling strategy and the reliability and validity of the research are addressed.

3.1 Research design

Three research sub-questions have been formulated to support the main research question. Sub question (1) refers to the need to analyse what is currently done with the potato peels in the Dutch potato processing industry. To answer sub question (2) it will be necessary to map out the ecosystem and the stakeholders that are involved in the possible transition towards a higher uptake of high-value substances from potato peels. Answering sub question (3) will require investigation of the techno-economic feasibility of transitioning towards a higher uptake.

By answering these sub-questions, a general answer to the main research question can be formulated. Figure 3 displays a schematic view of the problem statement linked to the proposed research and where the research questions are addressed. The yellow arrows indicate the data gathering needed for answering the questions, and the blue arrow indicates a theoretical framework that will be applied:

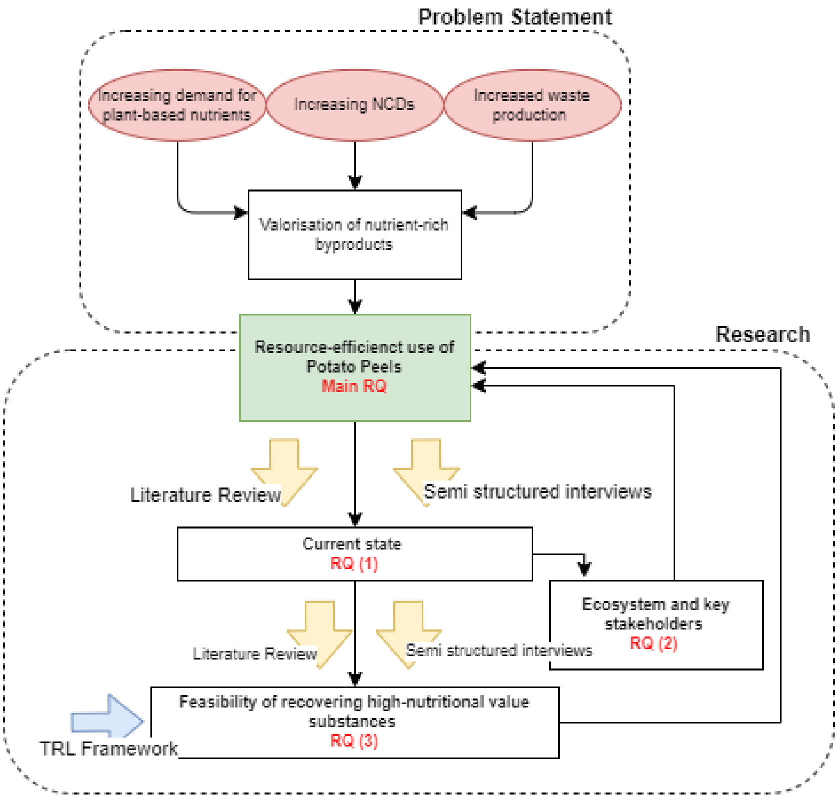

Figure 4 - Schematic view of problem statement related to the research and its research questions/theory/data gathering

This research will have a predominantly qualitative nature, as qualitative research can help to provide a contextual understanding of barriers to increase the uptake beyond quantitative data (DiCicco-Bloom & Crabtree, 2006). In this case, pinning down the factors to increase the uptake leading to better use of resources, make a contribution to knowledge based on interviews held with various stakeholders and a literature review. The following sub-sections describe what data gathering methods have been used, which stakeholders have been interviewed and how the research questions will be answered.

3.2 Data gathering

Primary data is gathered through semi-structured interviews with relevant stakeholders and experts in the potato industry. The choice to use semi-structured interviews is based on the idea that motivations, opinions and experiences of various stakeholders can be mapped (Flick et al., 2004). This is important as these can provide crucial insights that become more apparent in practice than in theory. Semi-structured interviews allow for the interviewee to speak freely and thus gives insights into what they see as important and relevant (Bryman, 2012). The latter is important as it might provide insights that have not been initially considered for this research. During this research, the author has interviewed different stakeholders, from diverse backgrounds, to gather data that helps to answer the research questions:

Potato processors

Interviewing potato processors is helpful for two important reasons. These stakeholders offer firsthand knowledge of the current potato processing methods, which is essential for understanding the basics of potato processing. Additionally, they can identify the practical and operational obstacles related to the handling of potato peels, offering valuable insights into the obstacles that any new technology or process might face.

Byproduct start-ups
Interviewing companies that have successfully valorised food processing byproducts is beneficial for a variety of reasons. First, these companies offer a clear perspective on effective methodologies and innovative approaches that have been used for the valorisation of various byproducts. They can share real-world lessons learned from the implementation and scaling of their technologies, which can be very helpful in understanding the critical success factors of such innovations.

Investors and business Incubators
These stakeholders can provide information about the financial and strategic aspects required for the successful commercialization of innovative technologies. They can provide a clear understanding of the investment criteria and funding reasons that support emerging technologies. This can then be directly applied to the scaling up of potato peel valorisation technologies. Furthermore, business incubators, in particular, can help with business development, scaling strategies, and network building. Engaging with these stakeholders enhances the research with practical, financial, and strategic insights.

Academia
Interviewing academics from universities with expertise in food, food production, circular economy, and healthy diets adds significant value to research on potato peel valorisation. These experts bring theoretical knowledge and research experience that can benefit this paper. They provide insights into the most recent scientific advances and theoretical frameworks relating to sustainable food production and byproduct utilization. By incorporating their academic perspectives, the research can combine technical feasibility with broader economic, and environmental goals.

Government bodies
These officials can provide information about the regulatory and policy frameworks that may affect the feasibility and scalability of this process. Their perspective helps to understand government support mechanisms such as possible subsidies or grants, as well as regional initiatives and additional regional data.

To get in touch with these stakeholders, a non-probability sampling method has been used, as for this research it is not the intention to test a hypothesis about a broad population, but rather to develop an initial understanding of a small and under-researched population (McCombes, 2023). Purposive sampling strategies are used to reach out to the most accessible and most relevant interview candidates for the semi-structured interviews. To ensure the protection of personal or sensitive data, answers of the interviewees have been further anonymized to safeguard their anonymity. This is done in accordance with EU data protection legislation, the General Data Protection Regulation and the Personal Data Act. The data will be obtained and stored merely for scientific purposes, and the interviewee is always able to see the research report afterwards. The table below displays a description of the participants in this research and their professional background.

Interviewee	*Description*
Participant 1	CEO of a byproduct valorisation company. Active for 10 years, start-up launched in 2021
Participant 2	Lead Innovation at a byproduct valorisation start-up. Already launched products in the market
Participant 3	Start-up analyst at a successful Business Incubator focused on agrifood innovations in the Netherlands
Participant 4	Experienced researcher at the Wageningen University & Research, published papers on relevant topics
Participant 5	Experienced researcher at the Wageningen University & Research, published papers on relevant topics
Participant 6	Project leader agrifood innovations at a governmental body in the Netherlands.
Participant 7	Energy Manager at a major potato processing company in the Netherlands
Participant 8	Environmental Manager at a major potato processing company in the Netherlands
Participant 9	Communication Specialist at a major potato processing company in the Netherlands
Participant 10	Director Agri Development at a plant-based ingredient and application company.
Participant 11	Central Procurement Manager at a byproduct valorisation and research facilitation
Participant 12	Representative at a development company focused on sustainable innovations

Table 1 - Anonymized interviewees and their roles

The data gathering through interviews is supplemented with a purposive literature review. As this approach emphasizes integrating information from multiple sources, this paper follows a more adaptable approach to selection and extraction (Cook, 2019). As this data gathering method merely supplements the primary data collection, the author does not deem it necessary to go with a more complex systematic approach. The two main academic search engines that are consulted are Google Scholar and Web Of Science, and are supported by the non-academic engine Google to delve into reports and stakeholder webpages. A snowballing approach is used to identify relevant academic papers and authors based on the references of already cited academic papers.

3.3 Operationalization

Prior to formulating the actual research questions, an extensive purposive literature review has been conducted to gain understanding of the processing of potato peels; the properties of the peel and its possible utilizations that have been published in academic papers. Initial search terms such as 'resource efficiency', 'food waste', 'potato peel valorisation', 'industrial symbiosis', 'recovery of bioactive compounds', 'potato processing', 'Biorefinery potato peel' and 'extraction methods potato peel' have led to a broad understanding of the subject and the possibilities for this research. With this in mind, the main research question and the corresponding sub questions were formulated, and henceforth suitable interview candidates were listed and approached. The semi-structured interview schemes that were formulated have been adapted to the different type of stakeholder.

The interviews have been analysed using a thematic analysis, which is ideal for qualitative research if the researcher is interested in understanding experiences, thoughts or behaviour (Kiger & Varpio, 2020). First, each interview was transcribed prior to analysing them. Next, the data analysis was done with a coding system carried out in the NVivo coding software. First it was important to go through each transcript and to identify the topics that occur and individual aspects which can broadly be related to the context of the research questions (Flick et al., 2004). When these topics and aspects became apparent, it was the goal to identify recurring topics, ideas and patterns among the various codes. These recurring codes were then categorized into different themes. It is important to ensure that the different themes appropriately represent patterns in responses (Flick et al., 2004). In this research, the three themes were linked to the sub questions: 1. Current situation 2. Ecosystem and stakeholders 3. Techno-economic feasibility. Data saturation was achieved as the last interviews did not provide any new comments and no new codes occurred (Saunders et al., 2017). The next paragraph describes the different approaches to answer each sub question with the goal to eventually formulate an answer to the main research question.

The objective of research question (1) is to establish a baseline understanding of the current applications of potato peels and to identify potential areas for improvement or to look for possible alternatives. The literature review has set the basis for answering this question, but additionally, potato processors in the Netherlands have been interviewed to get real-world insights into how they process their potatoes and respective byproducts. The interviewees also got questioned on alternative uses for their byproducts, based on findings from the literature review, and how they perceive these solutions.

An answer to sub question (2) is needed to identify the major stakeholders in the potato peel valorisation process. With this information the ecosystem of potato peel valorisation can be mapped. This provides insights on the impact of each stakeholder in this system from production, to market release. To answer this question the semi-structured interviews were used. Each interviewee was asked about their most important stakeholders and the ecosystem. The literature review was used for additional remarks.

The objective of the last sub question (3) is to examine the actual technical and economic feasibility of improving potato peel valorisation. This includes the analysis of the technology required for extraction, potential funding sources and potential costs. This question was answered with the input of various interviewees, with help of secondary data and by applying the TRL framework in the technology analyses. The latter was applied to evaluate the technologies involved in extracting and utilizing high-nutritional-value compounds from potato peels.

3.4 Reliability and validity

The ensure reliability, data collection should be as consistent as possible. In practice, for each interview specific behaviour and responses will be treated the same as in other interviews. This is done by being consistent in the phrasing of questions and ensuring that while gathering the data, the circumstances are the same for each interview to reduce the influence of external factors that might create variation in the results (Middleton, 2023). This can often be done by maintaining a neutral standing in the questioning instead of already leaning towards a desired outcome, this makes the data more reliable. When additional information emerged from the more spontaneous part of the semi-structure interviews, it was used as illustration of more particular drivers or constraints.

Internal validity is achieved by ensuring that the sample is diverse enough to represent different perspectives within the totality of stakeholder categories for this subject (Maxwell, 1992). External validity will be achieved if the research design can also be applied to other research when the methodology is followed in a similar pattern (McDermott, 2011). This research could also be applied to different byproduct streams in the food processing industry. However, some parts of the research will not be easily replicable as they focus exclusively on potato peel related issues and are focused on the Dutch market.

4. Results

In this chapter the results of the data gathering through primary data and the extensive literature review are defined. The chapter is divided into answering the four sub questions, which will are linked to the main question in the next chapter.

4.1 The current situation

How are potato peels currently utilized in food processing and other industries?

This section provides a baseline for what is currently done with the potato peels in the potato processing industry. This baseline sets the scene for the research, and is essential for assessing potential improvements and innovations.

4.1.1 The potato industry

The Netherlands currently ranks amongst the top 10 biggest potato producers in the world (Mickiewicz et al., 2023). Close to 6.5 million tonnes of potatoes were harvested in 2023, out of which 3.5 million tonnes were consumption potatoes (CBS, 2024). In the Netherlands there is a distinction between 3 types of potatoes: starch potatoes, seed potatoes and consumption potatoes (Berkhout et al., 2023). This research focusses on the consumption potatoes as these are subject to further processing. Most of the consumption potatoes are processed into a wide variety of products, mostly frozen products, but a small percentage gets washed and packaged directly (Janssens & Smith, 2016). The Netherlands has a large potato processing industry, and close to 95% is covered by the Vereniging voor de Aardappelverwerkende Industrie (VAVI) (VAVI, 2022; Berkhout et al., 2023). The VAVI is a Dutch potato processing collective, joined by six major potato processors.

According to the interviewees, once the potatoes are harvested they are transported from the fields, through warehouses, to the processors. The first step at the processing companies is to wash the potatoes, the potatoes are washed to eliminate entrained residues such as rocks, debris and soil. After the washing phase, the potatoes are sorted. The sorting is based on the size of the potato as different product types require different potato sizes. After this the potatoes are prepared for the peeling process. In the Netherlands most potatoes are peeled using a steaming process. Once washed, the potatoes are at room temperature and are to be transported to pressure vessels where the potatoes will be sealed off and steamed with temperatures between 180 and 200 degrees. The water below the peel starts boiling onto the colder potato, and when the pressure is then released in the vessel, the water condensates and the peels loosen. After the steaming phase, the potatoes are transported to a brushing machine and brushed to separate the peel from the flesh. Once brushed, the potato peels remain moist and can be further transported in tankers (Participant 7; 8; 9, 2024).

4.1.2 Peel processing

The research of Van Hout et al. (2020) mapped out the potato industry in the Netherlands and calculated that the potato peel accounts for almost 20% of the total raw product input. This means that last year roughly 700.000 tonnes of potato peel output was generated. Currently the potato processing industry in the Netherlands has two destinations for the potato peels. The option of landfilling the potato peels is prohibited and strictly regulated according to EU law, enforced by Dutch law (European Commission, 2023; IPLO, 2024).

The first, and most applied, option is using the potato peels for pig feed. Approximately 95% of the peels are stored and transported in tankers destined for pig feed (Janssens & Smith, 2016; VAVI, 2023). The peels are delivered in loads starting from 28 tonnes up to 35 tonnes. The peels are grounded and remain in a liquid slurry and are advised to be used within 6 months of storage in a silo or storage bunker. However, the peels can have a longer shelf life if the storage vessel is properly cleaned once or twice a year. As the peels are rich in starch and contain protein and crude fibre, they are well-suited for animal feed (Looop, 2023; Duynie, 2024). The potato processors, generating the peels, work in accordance with the ISO 14001, which promotes environmental protection (ISO, 2024), and the peels have to be processed according to the Good Manufacturing Practices + Feed Certification (GMP+FC) to be allowed to use as animal feed (GMP+ International, 2024; Participant 6; 7; 8, 2024).

The other, lesser used, option is using the potato peels for the production of biogas. Once the peels have been removed from the flesh, they remain in a moist state. These peels are then transported to a biogas motor onsite that uses anaerobic digestion to produce biogas (Soltaninejad et al., 2022; Participant 8, 2024). The potato peel slurry still holds a dry matter percentage ranging between 10 to 15 percent (Looop, 2023; Duynie, 2024), so it can directly be converted to biogas. Drying the slurry is only required with masses having a dry matter percentage of 25 and higher (Kuikman et al., 2000). The digestion process turns 75 to 80 percent of the organic dry matter into biogas. This creates two outputs, the biogas itself, and a wet digestate. Since its a wet anaerobic digestion process, there is a higher amount of waste water but a smaller amount of digestate. The digestate that remains can be re-used as a composting material, but this generates additional costs (Luning et al., 2003). The biogas output can be used to produce heat and electricity for use in engines and fuel cells (Participant 8, 2024). Additionally, biogas production requires a high amount of fixed costs and consistent variable costs due to machinery, maintenance and energy costs (Obileke et al., 2022).

Using the potato peels as a resource for pig feed is currently the most commonly used processing method. Potato processors and representatives from governmental bodies explained that this preference is reinforced by the ideology of Moerman’s Ladder, a framework that prioritizes higher-value uses for byproducts. The framework ranks uses for byproducts from most desirable to least desirable, the higher the ranking, the more sustainable the option of further processing the byproduct (Eriksson et al., 2015):

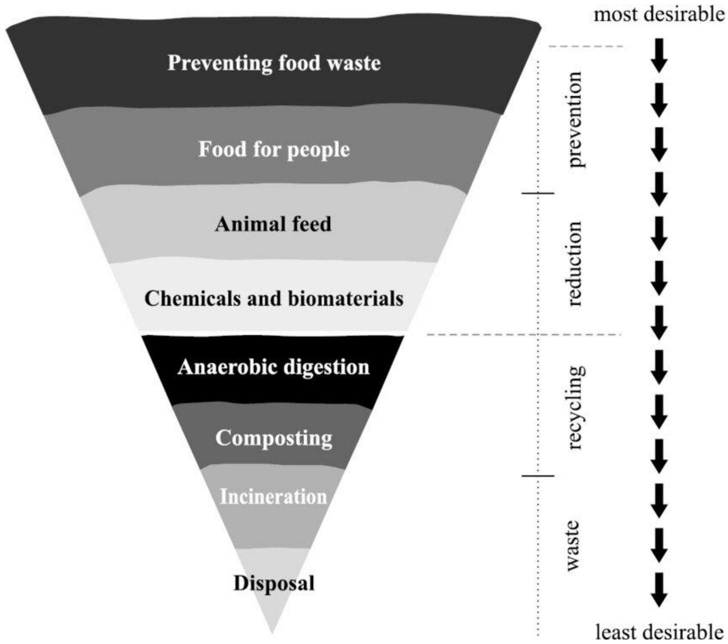

Figure 2 - The Moerman's ladder framework

Animal feed is ranked higher on this ladder than biogas production because it directly contributes to the agricultural value chain by providing nutritional feed rather than being used to generate energy (Eriksson et al., 2015). As the Moerman's ladder suggests, preventing food waste is the most desirable option. However, potatoes are currently the third most important food crop for human consumption due to its food security. Food security is based on four dimension: Food availability, access, stability and use and quality. The potato matches all these constraints (Devaux et al., 2021), hence a reduction of potato cultivation, and thus completely preventing the creation of potato peel residual flows, is not desirable (Participant 3; 4; 6; 7, 2024).

The second best solution according to Moerman's ladder would be food for people. Using potato peels in food products for human consumption improves resource efficiency by extending the lifecycle of food resources and reducing the need for additional raw materials (Rood et al., 2017). Furthermore, converting potato peels into human food products can help to improve food security by providing additional sources of nutrients. It requires that the peels meet food safety standards and are free of contaminants (Participant 8; 11, 2024), which may necessitate additional processing and investment. However, the potential market value of such innovative applications may offset these costs (Rood et al., 2017)

On the other hand, whereas it is good for reducing waste and recovering energy, using peels for animal feed or biogas does not offer the same degree of direct human benefit, economic return, or environmental efficiency as using them for human consumption (Rood et al., 2017). Thus, under the sustainability and circularity concepts described by Moerman's ladder, giving potato peels priority use in human food products represents the best use of them. Governmental bodies in the Netherlands actively supports this viewpoint by providing various incentives to encourage the valorisation of byproducts for higher-value applications. These incentives are part of a larger strategy to improve resource efficiency and sustainability in agricultural practices, which aligns with regional goals to promote a circular economy (Participant 6, 2024). Participant 6 added that biogas for them has the least value and even though pigs have an important role in the food system, they still aim to make the best use of the available valuable substances according to their ‘feed-to-food’ principle. There are alternatives for pig feed which is why the focus is on establishing a sustainable human food system.

4.2 Stakeholders and the ecosystem

What agency and influence can the stakeholders in the Dutch potato by-product valorisation ecosystem have?

This section provides a comprehensive understanding of the stakeholder landscape, their roles, interactions, and their collective impact on valorising potato by-products in the Netherlands.

4.2.1 The system

The Netherlands is part of the Platform for Accelerating the Circular Economy (PACE), in which 40 member states, companies and organisations work together to ensure a global circular economy. To meet the targets set by PACE, the Netherlands started a government-wide programme in 2016 to achieve ‘a circular economy in the Netherlands by 2050’, meaning a waste-free economy by 2050 (Dijksma et al., 2015). The programme has since then been updated with a report for the years 2023 to 2030. The report focusses on the use of raw materials for Dutch production and consumption, and has four measures set out to be achieved: 1. Reducing raw material usage, 2. substituting raw materials, 3. extend product lifetime and 4. high-grade processing (Rijksoverheid, 2023).

The innovation of further valorising potato peels fits the scope of these measures, however, to achieve such a transition, a collaboration among businesses, authorities, the public and educational institutes is necessary (Rijksoverheid, 2023, Participant 1; 2; 3; 6, 2024). These collaborations together form an innovative ecosystem which can be defined as the collaborative arrangements through which firms and organisations combine their individual offerings into a coherent, customer-facing solution (Granstrand & Holgersson, 2020 & Participant 3, 2024).

4.2.2 The stakeholders

To map out these stakeholders and their relationships, participants of the semi-structured interviews were questioned on their most important stakeholders and their roles in the ecosystem of valorising by-products in the Netherlands. The following stakeholder categories were listed as essential to accelerate the transition. Within each category, examples are provided of organisations that have been mentioned by the participants.

<u>Start-ups and Corporations</u>
These stakeholders analyse market trends and develop innovative ideas that make use of byproducts in economically feasible ways. Corporations, especially those in the agricultural and food processing sectors, engage in valorisation strategies to promote sustainability, minimize waste, and enhance profitability by converting waste into valuable products. *Examples of relevant stakeholders are: PectCof, Peel Pioneers, Unilever, Cargill*

<u>Experts and research institutions</u>
Academics and researchers contribute scientific research and technological development required to advance byproduct valorisation techniques. Their research contributes to the knowledge of the properties of byproducts, the enhancement of methods for their conversion, and the assurance that these methods are both environmentally sustainable and economically feasible. *Examples: Normec and Wageningen University and Research*.

Investors

Investors, such as venture capitalists, angel investors, and public funding bodies, supply the necessary funds needed to expand valorisation technologies from the laboratory to the market. They evaluate the risk and potential financial gain in valorisation projects, and their assistance can be vital for startups and companies seeking to engage in the byproduct industry. Their funding decisions frequently depend on the perceived profitability and sustainability impact of these projects. *Examples: OostNL, RVO, Future Food Funds, Brightlands Venture Partner, Peakbridge*

Business incubators and accelerators

Business incubators and accelerators promote cooperation among different actors in the byproduct valorisation ecosystem. They offer platforms for information exchange, policy influence, and setting standards. These organizations have the ability to promote beneficial regulatory conditions, offer training and assistance to corporations and start-ups, and facilitate the spread of effective business practices and successful models throughout the industry. *Examples: Start-Life, Food Valley NL*

Government and regulatory bodies

Government agencies and regulatory bodies influence the operating conditions of byproduct valorisation initiatives through the enactment of laws, regulations, and incentives. They have the ability to establish policies that promote the adoption of sustainable practices and the utilization of byproducts, such as providing subsidies for environmentally friendly technologies, offering tax incentives, and allocating grants for research. Furthermore, they guarantee that these practices comply to health, safety, and environmental regulations. *Examples: PBL, Provincie Gelderland, Dutch Ministiry of Agriculture*

Agricultural producers and processors

Agricultural producers and processors play a vital role in byproduct valorisation as they are the main creators of these byproducts. They make the choice of handling these byproducts as possible resources or as waste. Their participation is crucial in directly implementing sustainable practices at the source or supplying the residual streams for further byproduct valorisation. *Examples: Agristo, McCain, Aviko, Avebe*

Technology providers

Technology providers create and distribute the essential equipment and technology needed to convert byproducts into usable forms. Their goal lies in developing advanced machinery, techniques, and systems that can optimize efficiency, minimize energy consumption, and maximize the production of valuable products derived from byproducts. *Examples: Cosun, Biobase Europe, NIZO food research*

Consumers and end-users

The success of products created from valorised byproducts is ultimately determined by consumers. Their approval and desire for these products can influence market patterns and motivate producers and corporations to invest in the valorisation of byproducts.

4.2.3 The innovation ecosystem

The innovation system consists of a sequence of interconnected stages that convert innovative concepts into tangible and impactful market solutions (Lager, 2010). The process starts with idea generation, wherein stakeholders, including researchers, entrepreneurs, and end-users, collaborate to identify opportunities and engage in creative thinking to develop potential solutions that align with specific needs or market gaps (Participant 3; 6, 2024). The government has a promoting role in this phase by initiating nationwide programmes such as the 'a circular economy in the Netherlands by 2050' (Dijksma et al., 2015; Participant 6; 12, 2024).

After the formulation of ideas, the idea development stage focuses on the process of transforming these ideas into concrete concepts or prototypes. Start-ups and entrepreneurs build on the knowledge of researchers and experts, and start to develop the idea (Participant 1; 2; 3, 2024). This is done by the support of business incubators and tech providers, who can support the idea by utilizing their network and their knowledge of the industry .

After the idea development, the project implementation stage commences. This involves scaling up the prototypes to full production levels, creating supply chains, and establishing the required production infrastructure. Effective scaling up requires funding and support by business accelerators and private investors, the knowledge and assets of technology providers and the input of resources by the agricultural sector (Participant 3; 4; 12, 2024).

The project launch stage involves the introduction of the product or service to the market. It contains marketing and distribution strategies aimed at reaching potential consumers. In this stage funding can be provided by private investors, or larger corporation can opt for an acquisition of the project as they already have an extensive network and market (Participant 3; 12, 2024).

The last stage, the continuous impact and feedback**,** focuses on maintaining the impact of the innovation and implementing ongoing feedback. This involves closely observing the effectiveness of the product or service, collecting consumer and end-user input, and implementing improvements. The objective is to guarantee the long-term success and relevance of the innovation (Participant 3, 2024). Figure 5 shows the different innovation stages together with the relevant stakeholders and their role within this system.

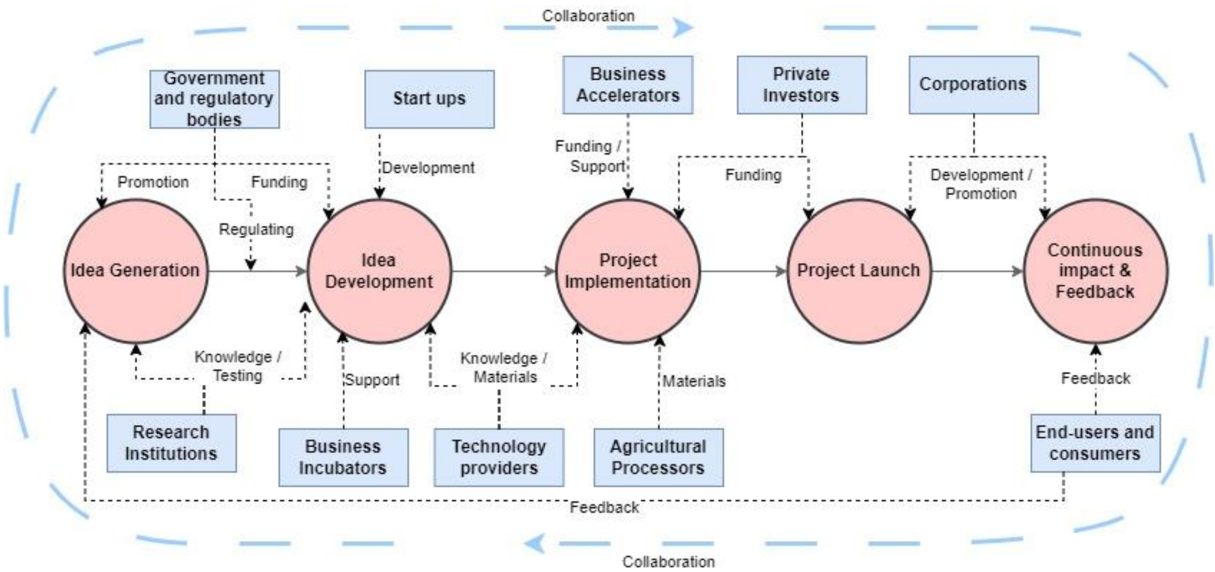

Figure 3 - The stakeholders and their roles in the valorisation of byproducts in the Netherlands

4.2.4 Key challenges and opportunities

Participants of this research were also questioned on the challenges and opportunities in this ecosystem. When talking about challenges, the regulatory hurdles were often mentioned. The goal of valorising the potato peel is to eventually process the won valuable nutrients into novel food products. However, the novel food law in Europe is strict and it can take up to 2 to 5 years for a product to be authorised by EU-law (Participant 1; 2; 3; 6, 2024). This waiting time can result into a decline of investments and interest in the product.

Another significant challenge is the scaling up of the technology. A pilot can be successfully tested on a small scale, but that does not automatically mean that it works on a larger scale (Participant 1; 3; 10; 11, 2024). Developing and scaling up technologies that can efficiently and cost-effectively valorise byproducts requires a lot of research and investment (Participant 1; 3; 10; 12, 2024). Investors are also less willing to commit to the project of the technology is still in its early technology readiness levels (Participant 1; 3; 12, 2024)

Economic viability has also been mentioned for not further valorising the potato peels. The potato processors currently have a solution for their peels, which are mostly destined to pig feed. This makes them reluctant to adapt to a new system at the processing sites. The high costs associated with processing byproducts due to new machinery, new markets and a new supply chain must be offset by the value of the products, this is currently not guaranteed (Participant 7; 8; 9, 2024). This hints towards the idea that the valorisation should be implemented by parties outside of the current potato processing industry.

Additionally, when processing potatoes the output of potato peels is in a wet slurry form (Participant 7; 8; 9, 2024). The moist level is not an issue if the peels are destined for pig feed or biogas production, but it becomes a challenge when its intended for food products. The extraction process of bioactive components can be less efficient due to moisture and temperature differences compared to extraction from dry materials, as it can degrade the phenolic compound properties. It can also effect the storage, handling and transportation of the peels, which can lead to increased production costs. (Tseng & Zhao, 2012; Rood et al., 2017; Gaudino et al., 2020; Participant 7, 2024). The moisture in organic matter can also lead to rapid microbial growth and spoilage, and as these peel are subject to food processing, maintaining quality and safety standards is critical (Participant 10; 11, 2024)

On the other hand, the Netherlands does provide an elaborate ecosystem to initiate concepts such as potato peel valorisation. The Dutch government actively supports sustainability initiatives by offering a range of incentives, including subsidies, grants, and tax benefits, to companies that engage in byproduct valorisation (Participant 1; 4; 6, 2024). This fosters an encouraging environment for businesses to allocate resources towards the adoption of innovative technologies. Besides the government, there is a stable system of collaborative ventures between knowledge institutes, business incubators and accelerators in the Netherlands, that can further support these initiatives with their extensive network, knowledge of the industry and their supporting tools (Participant 1; 3; 11, 2024)

Another opportunity that has been mentioned is the fact that byproduct valorisation initiatives do comply with current sustainable market trends (Participant 6, 2024). It is tested that these potato peel extractions can be done through various extraction methods such as UAE or MAE, and that there is a demand for sustainable and circular products from the industry but also from the end consumers. This makes these initiatives more likely to attract investors, but also provides a certainty that there will be demand for the final product (Unruh et al., 2016).

In addition, there is a high amount of potato peels available in the Netherlands. Last year more than 7 million tonnes of potatoes were cultivated. There are 18 major potato processing facilities in the Netherlands, which are scattered throughout the country (Janssens & Smith, 2016; van Hout et al., 2020). This geographic distribution lowers transportation costs, guarantees a steady supply of potato peels, and can facilitate regional valorisation efforts

(Donner et al., 2021). Having this steady stock allows for economies of scale in processing technologies and as the valorisation technologies become more efficient, the costs can be spread over a larger amount of goods (Kenton, 2024).

4.3 Feasibility of innovation

What is the techno-economic feasibility, including Technology Readiness Levels, of implementing the recovery of high-nutritional-value substances from potato peels?

This section assesses the validity of scaling up extraction methods for the extraction of high-valued substance from potato peels. The technology readiness level scale is applied to determine the current status and the scalability.

4.3.1 Extraction methods

To extract substances from potato peels a multipurpose biorefinery model, as depicted in figure 2, can be applied. Currently the two most used methods in the biorefinery extractions are solid-liquid extraction (SLE) and ultrasound-assisted extraction (UAE) (Almeida et al., 2023). When considering SLE, it is important to use a green solvent instead of conventional solvents such as acetone or methanol. Using these conventional solvents is not environmentally friendly as these solvents contain a high amount of toxics, which makes it unsafe for the further processing of food applications (Participant 11, 2024). A suggested green solvent is a natural deep eutectic solvent (NADES), NADES are cheap, easy to prepare and have very low toxicity levels (Rodriguez-Martínez et al., 2021; Jimenez-Champi et al., 2023). However, using NADES is a fairly new method, and has thus far only been used on a lab scale, not on an industrial scale (Chemat et al., 2019).

UAE on the other hand is considered a more sustainable extraction method. Compared to SLE, there is a higher recovery yield of valuable substances; a reduction in solvent consumption; a greater repeatability; easy to scale up and most notably a lower treatment time (Zhang et al. 2020; Rodriguez-Martínez et al., 2021; Almeida et al., 2023; Jimenez-Champi et al., 2023). A lab test ran by Zhang et al. (2020) demonstrated comparable yield recoveries between SLE and UAE, but the UAE only took 30 minutes while the SLE lasted for 24 hours. It is worth mentioning that after the extractions the remaining residue can still be treated with anaerobic digestion to create biogas. After digestion it is also still possible to use the digestate for composting purposes (Almeida et al., 2023; Participant 8, 2024). Microwave-assisted extraction (MAE) is a relatively new technology that uses a microwave that rupture cell walls which allows for the extraction of high-value substances. While this technology has been successfully used for extraction of bioactive compounds in different residual streams, mainly plant foods, they have not been documented yet for the extraction of potato peels (Jimenez-Champi et al., 2023). Just like UAE, MAE demonstrates higher extraction yields in shorter periods, and is more adaptable to various scales from lab to industrial compared to SLE (Almeida et al., 2023)

With the current extraction methods available, most efforts so far have been put into the extraction of polysaccharides, phenolic compounds and glycoalkaloids. Potato peels, with minor supplementation, are suitable for the production of single cell protein, (Taskila et al., 2018) and by using a biorefinery model they can be extracted from the waste water which is left after starch extraction (Torres & Domínguez, 2019; Kot et al., 2020).

4.3.2 Technology readiness level

The TRL scale helps to identify how close a technology is to full-scale industrial application. It can help to determine the scalability of such technologies, which on terms helps to attract investors for projects determined to valorise byproducts. In table 1 valorisation technologies are depicted together with their corresponding TRL:

Technology	Output	Technology Readiness	Reference
Food processing	Animal feed	TRL 9	(Participant 7; 8; 9, 2024)
Anaerobic Digestion	Biogas	TRL 9	(Participant 7; 8; 9, 2024)
Extraction (waste water)	Starch	TRL 9	(Ratnayake & Jackson, 2003; Rodriguez-Martínez et al., 2021; Avebe, 2022; Almeida et al., 2023)
Extraction (hydrothermal treatment)	Starch	TRL 6	
Extraction (SLE – UAE-MAE)	Phenolic compounds; Glycoalkaloids	TRL 4 – 6	(Hossain et al., 2014; Singh et al., 2019; Helal et al., 2020; Sampaio et al., 2020; Zhang et al., 2020; Almeida et al., 2023; Jimenez-Champi et al., 2023)
Extraction (waste water)	Protein	TRL 4 – 5	(Priedniece et al., 2017; Torres & Domínguez, 2019; Kot et al., 2020; Chauhan et al., 2023)

Tabel 2 - Valorisation technologies and their TRL

The technologies food processing into animal feed, and the anaerobic digestion into biogas are methods that are currently implemented in an operational environment. Most potato processors in the Netherlands are either using their peels for animal feed or biogas production. This application indicates that the technology is already adopted by the industry and thus has reached the maximum technology readiness level of 9.

Starch is already successfully extracted from potatoes. Starch is extracted from waste water that is used during the processing of potatoes (Almeida et al., 2023). The water is subjected to sedimentation and then an extraction through decanting, centrifugation, and freeze drying is performed to obtain crude starch (Anbuselvi & Reji, 2018). In general, potato starch is used for supporting overall texture of food products (Semeijn & Buwalda, 2018) and is already used in an operational environment which results in a TRL of 9. Starch extraction through hydrothermal treatment has so far only been executed through pilots, but the technology has already been successfully demonstrated with comparable byproducts such as peanut shells, melon peels and vine shoots (Rodriguez-martinez et al., 2021). This extraction technology therefore yields a TRL of 6, as it has already been demonstrated in an relevant environment.

The extraction of phenolic compounds, glycoalkaloids and protein from potato peels with SLE, UAE and MAE is still in its earlier TRL stages. Lab tests with potato peels have been successfully completed on small scales, and the technologies have been validated, and sometimes demonstrated, in other relevant environments with different residual streams but not with potato peels, thus these extraction methods have a TRL of 4 - 6 (Sampaio et al., 2020; Zhang et al., 2020; Almeida et al., 2023; Jimenez-Champi et al., 2023). The potential of these extractions is promising, but further research and testing is required to determine the actual scalability of these technologies.

4.3.3 Economic feasibility

The economic feasibility of extracting substances from potato peels such as phenolic acids and glycoalkaloids seems promising, but it involves certain risks and considerations (Donner et al., 2021). The existing literature collectively indicate that the valorisation process can be economically feasible, especially when utilizing integrated biorefinery models that maximize the extraction of multiple products (Almeida et al., 2023). However, the success factor is dependent on a variety of factors, including operational scale, market demand, geographical factors, supply of resources and technology readiness (Wu, 2016; Cristóbal et al., 2018; Donner et al., 2021; Participant 6; 8, 2024).

The Advanced extraction techniques UAE and MAE have demonstrated high efficiency and scalability (Almeida et al., 2023) and their TRL ranging up to level 6 indicates that they are getting close to commercial implementation. The initial capital investment necessary for establishing these extraction facilities is substantial compared to SLE, which requires simple equipment and does therefore not require a relatively high initial capital investment (Gaudino et al., 2020). However, the higher extraction yield and lower extraction times reduce operational costs when the economies of scale is achieved and will be therefore be a more feasible option on a larger scale.

The potential for generating revenue is considerable, as there is a strong market demand for natural antioxidants and bioactive compounds derived from potato peels (Valanciene et al., 2020). Nevertheless, the operational costs, specifically the costs of solvents and utilities, can be significant (Cristóbal et al ., 2018). When comparing the utilization of potato peels to other residual streams such as citrus peels, several notable factors become apparent. The market demand for phenolic acids and glycoalkaloids, while significant, is not as high as for the products derived from citrus peels. Citrus peel valorisation is higher in demand because it can be used to produce a variety of valuable products such as essential oils, pectin, and also phenolic compounds. These products have higher market prices, resulting in better return on investment (ROI), 114.2% compared to 2 to 10% of potato peel valorisation, and a shorter payback time (PBT), potato peels have a high PBT of 16 years, under medium price conditions (Cristóbal et al ., 2018; Caldeira et al., 202; Almeida et al., 2023). The extraction methods for citrus peel are both cost-effective and environmentally friendly, as they employ solvent-free technologies that effectively lower operational expenses. Both potato and citrus peel extraction technologies, namely ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE), have reached similar technology readiness levels (TRLs) of 6-7. This indicates that both technologies are close to being commercially viable. The operational costs are also higher for the valorisation of potato peels due to significant solvent use (Cristóbal et al ., 2018; Caldeira et al., 2020).

Economically, it is feasible to convert potato peels into high-value substances, particularly when scaling is optimized and market conditions are favourable. In contrast to other residual streams, such as citrus peels, which offer a more appealing economic case due to their higher market demand, lower operational costs, and better economic metrics, it is subject to higher risks and lower profitability. In order to improve the appeal of potato peel valorisation, it is important to implement considerable improvements in cost management strategies, process efficiencies, and market conditions. It will be essential to integrate advanced extraction methods and optimize the biorefinery model to maximize value recovery from potato peels in order to improve economic viability.

5. Discussion

In this chapter, the main outcomes of the results chapter are discussed and recommendations are formulated to increase the uptake of high-value substances from potato peels.

The current processing methods of the potato peel in the Dutch potato industry are not optimal in achieving its highest resource efficiency. Applying the Moerman's ladder to the potato peel valorisation efforts in the Netherlands, pig feed and biogas production, suggests that there is still room for improvement. There are two methods perceived as more resource efficient: Extracting high-value substances from the peels destined for human food processing and the total prevention of the byproduct stream. The latter is rated the highest on the Moerman's scale, but is also difficult to achieve. Potatoes are a common food in the Dutch diet, and are mostly consumed in processed forms. Thus, potato peel residual flows will likely be unavoidable. Dutch governmental bodies and corporations, however, could possibly promote the eating of the potato in its natural form, washed and not processed, to limit the amount of potato waste generated. These initiatives have nevertheless not been promoted yet. Therefore, the most resource efficient and achievable valorisation process of potato peels would be the extraction of high-value substances from the peels using a multipurpose biorefinery model. This extends the lifecycle of the peels and less raw materials are needed to gain these substances, which is in line with current Dutch governmental circular programmes.

Looking at the ecosystem of the valorisation of byproducts industry in the Netherlands, it can be concluded that there is a strong and supportive system to transition into more efficient valorisation efforts. There are extensive collaborative networks established in the Netherlands that can support these transition efforts through knowledge sharing, funding and access to partnership networks. These collaborations exist between governmental agents, business incubators, business accelerators and experts from research institutes and technology developers. The Dutch government plays a key role in this transition as they can establish policies that promote the adoption of sustainable practices through subsidies, tax reductions and grants. Business incubators also play a key role as they have access to stakeholders that other actors might not have and thus can support starting initiatives to further scale up their efforts of valorising potato peels. Lastly, startups and corporations play a key role in this transition as they need to initiate the efforts to start ventures that are willing to extract high-value substances from potato peels. This is important as the potato processing industry is currently not willing to adopt a new system due to initial capital investments and producing costs. They currently have their valorisation methods, pig feed and biogas production, and are less likely to adopt a new system.

The technical feasibility of extracting high-value substances from potato peels has also been researched and a multipurpose extraction biorefinery is the most viable approach. Starch extraction technologies are already in their TRL of 9 and can be directly applied for commercial practices. Extracting phenolic compounds, glycoalkaloids and proteins from potato peels is more challenging. The SLE extraction technology is most commonly applied for such extractions but it is important to note that green solvents such as NADEs need to be considered to comply with safety and quality regulations set by the EU, as these substances are ultimately destined for human consumption. Green solvents are a fairly new concept, and more research into the usage of green solvents is needed to determine its operational efficiency. SLE uses a lot of solvent, and efficient use of green solvents could substantially decrease operational costs. By extending the knowledge on green solvents, they are more likely to be used in actual potato peel extractions. There are however alternatives for the extraction biorefinery. UAE and MAE are extraction methods that yield higher recoveries in a substantial shorter timeframe. These methods require a relative higher initial investment capital, but their efficiency outweighs the initial investment over a longer period compared to SLE. SLE, UAE and MAE have a TRL ranging from 4 to 6. This indicates that the technologies are not yet ready for the production of commercial end products.

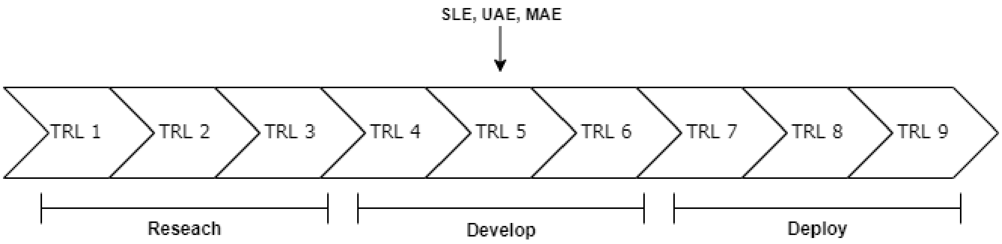

Figure 4 - Current stage of SLE UAE and MAE on the TRL scale

These technologies are still in their developing phase. They have been lab tested, pilots have been performed and demonstrations under comparable conditions with other byproducts have been done. Even though there is a supportive ecosystem; the transition links with current sustainable market trends; there is sufficient stock in the Netherlands and a good geographic spread, the scalability of the extraction technologies still remains an issue. The scalability is influenced by long lead times due to legislation; a need for further research on the efficiency of the extraction technologies; the handling of the moist peel output and the under researched economic feasibility. To counteract the restriction for further upscaling, the reviewed literature and the results of the semi-structured interviews provide the following recommendations.

The long lead time of the product development due to legislation should be clearly formulated to investors and interested stakeholders. It is important to start the process of passing legislation as early as possible to minimalize dull waiting times.

Experts and research institutions should further indulge in optimizing the extraction methods so that costs can be reduced when the technology is applied on a broader scale. This makes it more attractive for entrepreneurs and investors to engage in byproduct valorisation.

Due to the moist peel output, biorefineries should be established close to the processing sites as this can significantly decrease costs associated with handling, transporting and the supply chains. It is also advised to not store the peels longer than 6 months due to degradation. Picking the right geographical location is therefore necessary for cost effectiveness, fortunately the processing sites in the Netherlands are evenly distributed and therefore provides a lot of possibilities.

Furthermore, a more comprehensive understanding of the economic feasibility when upscaling is needed. The extraction methods are tested, and similar byproduct valorisation efforts have proven to be profitable. It is therefore recommended that research institutions, technology providers and business accelerators collaborate in their efforts to gain a better understanding of the economic feasibility. Once this is established, it becomes more appealing for private investors and corporations to engage in the upscaling of valorising potato peels.

6. Conclusion

This researched delved into the valorisation of potato peels in the Netherlands. The research question ''*How can the uptake of high-nutritional-value substances from potato peels be increased to enhance resource efficiency?''* has been addressed through a comprehensive examination of current potato peel valorisation practices, technological advancements and stakeholder influences in the valorisation of potato peels. The necessary data to answer this question has been done through semi-structured interviews with various stakeholders in the industry supported by an extensive literature review.

The results suggest that it is possible to increase the uptake of nutritious compounds found in potato peels by implementing technological improvements in extraction methods, promoting collaboration among stakeholders, and establishing a supportive regulatory framework. Utilizing advanced extraction and processing technologies in a multipurpose biorefinery has demonstrated the ability to maximize the extraction of valuable compounds from potato peels, thus improving the efficiency and economic viability of these processes. However, the scalability of such processes still requires further research in order for it to be deployed in an operational environment.

To conclude, The valorisation of potato peels presents a substantial opportunity to shift towards a more sustainable and efficient utilization of resources in the Netherlands. To fully harness the potential of potato peels as a resource, it is necessary to adopt innovative technologies, involve a wide range of stakeholders, and take advantage of favourable policies and ecosystem. This initiative not only supports worldwide sustainability objectives but also provides economic advantages, improves food security, reduces waste production and capitalises on food trends, driving the Netherlands towards a more circular and resource efficient economy.

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