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# Intelligent potato frying: Time to say goodbye to the "good old" processing strategies

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ABSTRACT

Potato chips production is a traditional food process. To achieve uniform product quality, raw materials are usually rigorously sorted. Traditionally, the process is conducted in a single stage approach leading to high quality losses. Recently, dynamically optimized frying processes have been found to result in higher product quality. Consequently, industrial continuous deep-fat fryers convey potato disks through several zones pre-set at different temperatures.

However, these improved systems still do not take the variabilities in frying kinetics among potatoes into consideration. To address this issue and decrease uncertainties in end-product quality, frying conditions of each zone must be optimized, physiochemical properties of the various raw tubers and their frying kinetics taking into account.

This paper, therefore, presents a novel approach for an intelligent frying process with embedded computer vision systems providing continuous monitoring of product quality and, therefore, facilitate dynamic control of frying conditions in order to meet desired quality attributes in the final product. An extensive literature review of the key physiochemical attributes of raw potato tubers is presented, followed by an introduction to novel pre-treatment technologies, and the importance of optimal frying conditions. An overview of the potentials for using computer vision systems for the assessment of said quality criteria is given, followed by a detailed description of the envisioned frying process. The paper concludes that the realization of intelligent frying processes necessitates the development of fully fledged digital twins of the process and the products, combining physics based and data driven modelling with real time sensing and control.

Terminology: Chips refer to thin slices of potato while French fries refers to wedges/stripes.

## Introduction

Unique sensorial attributes such as taste, color, and texture have made potato chips the long-standing king of snacks in the market [81]. Potato chips are mostly produced by immersion in hot frying oil which results in undesirable compounds, such as oil content and toxicants [107]. A high oil content has raised health concerns because of its role in the prevalence of cardiovascular diseases, obesity, etc [58]. Oil uptake is influenced by several factors such as dry matter content, porosity, surface area and roughness, frying conditions, oil type and its degradation among others [58]. Oil content is sub-grouped into structural oil (STO, absorbed during frying), penetrated surface oil (PSO, migrating into the flesh during cooling phase), and surface oil (SO, adhered to the surface). PSO accounts for the largest portion of oil content [58]. In addition to oil content, potatoes are highly susceptible to formation of hazardous components when they are exposed to high temperature processes such as frying. In this regard, acrylamide is considered as a toxicant and potential carcinogen found in the highest levels in fried potato products and coffee substitutes [92]. Acrylamide is an odorless, colorless, and water-soluble component formed through Maillard reaction where reducing sugars and asparagine play key roles [60]. Acrolein is another pathway by which acrylamide is formed when oil temperature goes

*Abbreviations:* HSI, Hyperspectral Imaging; PEF, Pulsed Electric Field; DT, Digital Twin.

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beyond its smoking point [60]. Apart from acrylamide, fried potatoes present furan which is potentially carcinogenic to human. It is formed when amino acids and sugars undergo thermal degradation and rearrangement, as well as when thermal oxidization happens in polyunsaturated fatty acids and ascorbic acid [62].

Many efforts have been made over the past decades to improve quality of fried potatoes which can be outlined as follows:

- Influence of physiochemical attributes of raw potato tubers on functional properties and end-product quality has been well investigated (Fig. 1). Potatoes with high dry matter content, for instance, have been found to result in lower oil uptake and crispy texture, whilst higher concentrations of reducing sugars induce formation of toxicants [81].
- Various technologies from blanching to ultrasound treatments have been applied to manipulate physiochemical properties of raw materials to guarantee critical quality and safety limits (Table 1).
- Optimization of frying conditions has been another topic of study by which either optimal static or dynamic frying conditions were found to improve end-product quality (Fig. 2).
- Potential of computer vision in quality inspection of raw and processed potatoes have been studied by researchers (Table 2).
- Integration of computer vision to develop improved process control systems.

Despite these significant efforts, what still needs to be done is to link the abovementioned findings together to make the whole process intelligent in which frying conditions during the process are optimally changed according to information gathered by monitoring systems. This gap likely exists because each discipline has addressed the issue within the parameters of its own field, whereas the complexity of the research topic requires an interdisciplinary approach, which brings together the knowledge of product quality, frying principles, optical imaging, image processing and machine learning, computer interfacing, dynamic optimization, process control and automation, hybrid modelling, and development of fully fledged digital twins. This paper intends to fill the research gap by utilizing a much-needed interdisciplinary approach towards the development, and use, of intelligent fryers to reduce the negative impacts on product quality that current potato chip production results in. In what follows, critical physiochemical attributes influencing end-product quality will first be discussed. Then, a survey will be given of emerging pretreatment technologies used to improve quality of potato chips. This will lead to the discussion of optimal frying conditions. It will be followed by computer vision applications in quality inspection of raw and processed potatoes. Finally, the future perspective of the frying process will be highlighted.

## Critical physiochemical properties of raw potato tubers.

The final quality of potato chips is highly influenced by physiochemical attributes of raw potato tubers (Fig. 1). The chemical composition depends on genotype, growing site, agricultural practices, harvesting date, and post-harvest storage [81]. Furthermore, chemical components vary within a tuber in such a way that dry matter content and reducing sugars, for instance, gradually increase, moving from the center towards the external parenchyma region [81]. Dry matter content, starch content, reducing sugars, and asparagine, among other chemical constituents, are of utmost importance that should be considered prior to any frying process. It has been well established that higher dry matter content is associated with lower oil uptake [12] and higher crispness in fried potatoes [1]. Potato tubers recommended for frying process should have a dry matter content higher than 20 % [44]. Starch accounts for ca. 65–80 % of the dry matter content which is the most important nutrient in potato. It consists of amylose (20–33 %), amylopectin (70–80 %), less than 0.4 % of minerals (phosphorus, potassium, calcium, sodium, and magnesium), and protein [20,25,84,102]. Amylose, amylopectin, and phosphorus are well known for their significant impact on physiochemical properties of starch. In this context, Tong et al. [104] found that pasting (starch mixed with water) properties of potato starch were significantly correlated with amylose and amylopectin; the thermal properties were only affected by amylopectin. The amylose has been found to restrict swelling power whilst it is claimed that swelling power is the property of amylopectin [53]. Vamadevan and Bertoft [108] observed a retard in swelling power when amylose content increased which in consequence starch granules disintegrated with delay and at higher temperatures. Besides the concentration of amylose and amylopectin, their structural type plays an important role in swelling power, pasting, and retrogradation properties

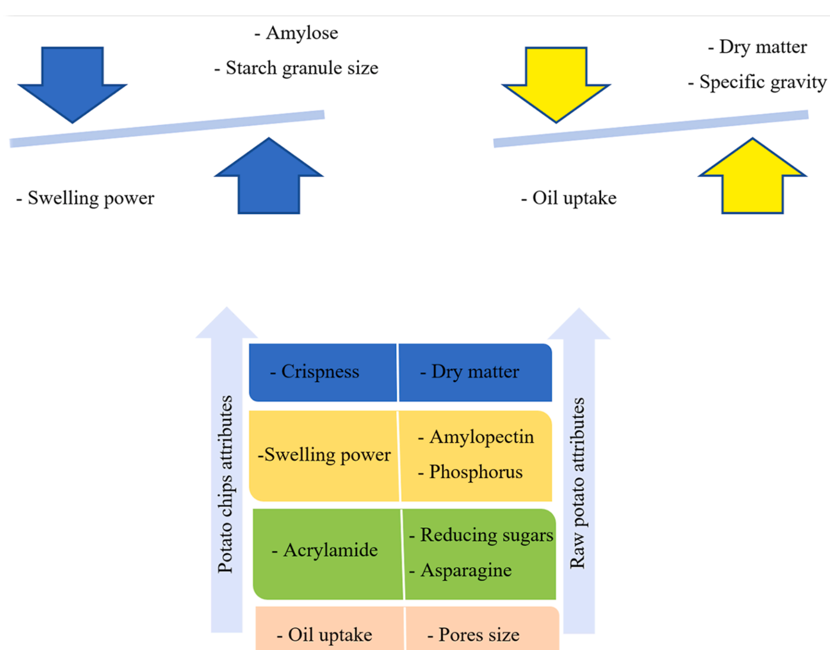


**Fig. 1.** Interaction between raw potato physiochemical attributes, functional properties, and potato chips quality.

**Table 1**
Potato chips quality improvement by application of pre-treatment technologies.

| Pretreatment | Observations | Limitation |
|---|---|---|
| Blanching | Acrylamide reduction up to 59 % [56]<br>Decrease (by 27.38 %) or increase (by ca. 20 %) in oil uptake [12,80]<br>Increase of lightness from 51.3 up to 61.1 and decrease of redness from 7.2 up to 2.4 [122] | Energy, time, and water intensive [37] |
| Pre-drying | Fat content decreased from 46 % to 24 % [11]<br>Hardness increased from 502.49 N to 836.28 N [119] | Low energy efficiency and lengthy drying time [100] |
| Coating films | Oil uptake reduction by 14.56 % [110]<br>Crispness increased from 2.24 N to 2.78 N [66]<br>Acrylamide reduction by ca. 77 % [52] | Significantly affect the moisture uptake due to barrier properties [10] |
| PEF | Reduction of fat content by 21.2 %, textural improvement but no significant change in acrylamide [118]<br>Acrylamide reduction by 31 % [30] | Intial high cost [24] |
| Ultrasound | Surface and structure oil contents decreased by 27.31 % and 22.25 % respectively [120]<br>No significant reduction in fat content [48]<br>Reduction in acrylamide by 34 % [79] | Limited technical information [38] |
| Pre-drying & coating films | Reduction in fat content from 20 % to 15 % [57] | N/A |
| PEF & blanching | Acrylamide reduction of 58.7 % but no significant change in fat content [91]<br>Lower fat content by 14 %, yellower in color, and 20 % lower acrylamide [117] | N/A |
| Ultrasound & pre-drying | Reduction in fat content by 51.76 % [119] | N/A |
| PEF & ultrasound | Reduction in fat content and Acrylamide by 16 % and 66 % [79] | N/A |
| PEF & coating | Fat content reduction by 57.86 % [48] | N/A |

[124]. Moreover, it is well known that starch granule size is proportional to amylose content; the larger the size of starch granules, the higher the concentration of amylose [18]. Regarding minerals, phosphorus is of more functional significance than the others [102]. Several studies have shown its positive correlation with more starch water absorption capacity, the onset and peak temperature of gelatinization, swelling power, peak viscosity, and breakdown among others [78,85]. Chen et al. [18] showed that phosphorus concentration is inversely proportional to starch granules size. Besides starch content, reducing sugars are pivotal in frying process such that their concentration must not exceed 2 % of dry matter content because of acrylamide formation [105]. Asparagine, an α-amino acid, is another key factor whose reaction with reducing sugars significantly induces acrylamide formation [99]. In addition to the chemical attributes, physical and structural characteristics of raw potatoes are of interest. In this context, specific gravity has been reported as an utmost important parameter which is strongly correlated with dry matter content [73] and firmness [1]; the higher specific gravity, the lower moisture content and oil uptake in fried potatoes [72]. Mealy-textured potatoes are more preferred for frying process than waxy ones [29] because they are more starchy than non-mealy ones [7]. Regarding microstructural properties, Liu et al. [55] showed that initial pores with a larger diameter result in more oil uptake. Furthermore, it

**Table 2**
Application of computer vision in quality inspection of raw and processed potatoes.

| Quality attribute | Technique | Wavelength | Reference |
|---|---|---|---|
| Raw potato | | | |
| Dry matter content | Spectroscopy | 1100 – 2000 nm<br>800 – 2500 nm | Escuredo et al. [27]<br>Camps and Camps [17] |
| Starch | HSI | 382 – 1004 nm | Wang et al. [109] |
| | Spectroscopy | 450 – 1000 nm | Farhadi et al. [28] |
| Reducing sugars | HSI | 400 – 1000 nm | Rady et al. [86] |
| | Spectroscopy | 450 – 1000 nm | Farhadi et al. [28] |
| Soluble solids content | HSI | 400 – 1000 nm | Shao et al. [93] |
| Asparagine | Spectroscopy | 4000 – 700 $cm^{-1}$ | Ayvaz et al. [13] |
| | HSI | 380 – 925 nm | Kjær et al. [46] |
| Processed potato | | | |
| Chromaticity | HSI | 400 – 1000 nm | Xiao et al. [112] |
| Acrylamide | Spectroscopy | 400 – 2500 nm | Adedipe et al. [3] |
| | Color camera | – | Arora et al. [9] |
| Fat content | Spectroscopy | 460 – 1040 nm | Pedreschi et al. [83] |

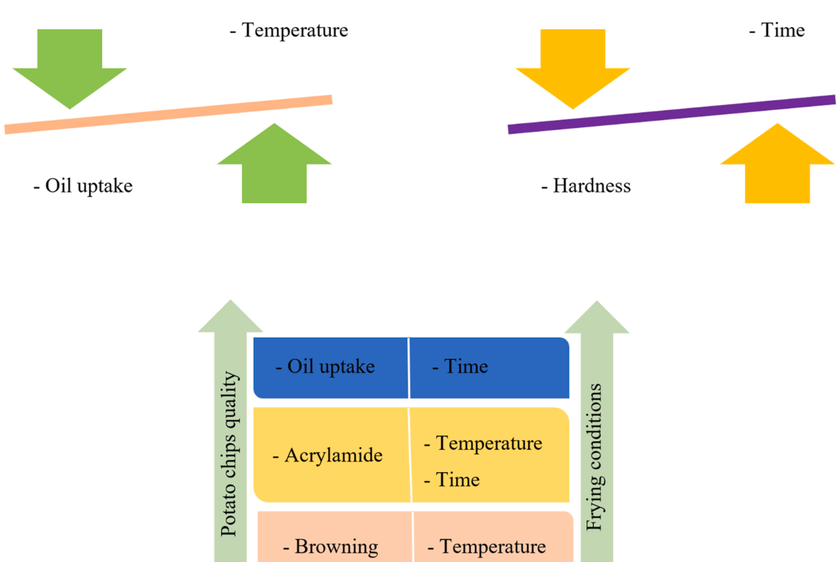


**Fig. 2.** Interaction between the frying conditions and potato chips quality attributes.

has been reported that starch granules size impacts on oil absorption, functional properties [18], and sensory attributes of fried potatoes [59].

The abovementioned attributes are amongst the most important ones whose significant impact on final quality of potato-derived products have already been established by many researchers; however, there are other attributes that could be taken into consideration. Pigmented potatoes containing higher concentrations of polyphenols, for instance, have been related to a lower formation of acrylamide than white-yellow fleshed potatoes [41]. Moreover, protopectin has been reported as the most influential non-starch polysaccharide on potato chips crispness [42]. It has been demonstrated that calcium and/or pectin pretreatments led to crisper and lower fat and moisture contents in chips [66]. Indeed, calcium cross-links to pectin molecules which results in potato-fried products of higher firmness [70]. From this point of view, the measurement of calcium and/or pectin concentrations in raw potato tubers could be considered as a control factor before any frying process.

In the light of above, it can be concluded that the analysis of raw potato tubers is pivotal to determine which tubers can be used in frying process, and which result in the highest quality product with the least negative impact upon health. Amongst the aforementioned physiochemical attributes, dry matter content, starch content, specific gravity, reducing sugars, and asparagine are the most conventional factors taken into account; however, an analysis of raw potato tubers for their starch content components (amylose and amylopectin), microstructural properties (starch granule size and porosity), and cell wall composition (pectin and calcium) can lead to a deeper knowledge of tubers, and thus, the production of potato-derived products with higher quality.

## Pretreatment applications to improve potato chips quality attributes.

Potato tubers are stored under cold conditions to avoid sprouting and diseases during prolonged storage. However, it results in cold induced sweetening and sugar accumulation. Prior to frying, potatoes are traditionally restored at 15 °C for some few weeks to reduce the concentration of reducing sugars [92]. Nowadays, there are more sophisticated ways of treating potatoes, including blanching, pre-drying, coating, pulse electric filed, ultrasound, high-pressure processing, and freezing. The most commonly used pre-treatments are presented in Table 1.

### *Blanching in water and solutions*

The immersion of foodstuff in hot water or their exposure to steam is referred to as blanching [121]. Blanching of potato slices in hot water has been related to the leaching of reducing sugars and/or asparagine which results in acrylamide reduction [30,60,91]. Liyanage et al. [56] blanched potato slices in distilled water and solutions of ascorbic acid, citric acid, calcium chloride, and several other chemicals at 65 °C for 5 min before the frying process. Blanching in distilled water resulted in the largest reduction of acrylamide content (up to 59 %). Blanching in hot water, at 100 °C for 4 min, duplicated its inhibitory effect on acrylamide formation; a reduction of 20 % occurred in the case of French fries [117]. A significant decrease in acrylamide formation happened when potato slices were immersed in water solutions of 2 % calcium chloride or 1 % citric acid as a result of diminishing reducing sugars and asparagine during soaking [26]. Moreover, some efforts have successfully been made to minimize acrylamide formation or its precursors by optimizing blanching parameters i.e. temperature and time [14,62,122]. In this sense, Mariotti et al. [62] found a frying temperature of 64 °C and frying time of 17 min as optimal blanching parameters which resulted in a significant reduction in ascorbic acids and reducing sugars which in consequence reduced furan and acrylamide formations by 91 % and 54 %, respectively. In the case of oil uptake, water blanching is expected to reduce fat content by gelatinizing the surface and/or activation of Pectin Esterase Enzyme (PME) which reduces porosity [12]. Nevertheless, its efficiency seems to be dependent upon process conditions such that blanching at high temperatures for a short time may result in higher fat content than unblanched ones [12]. According to Liberty et al. [50], prolonged blanching at low temperature is superior to a short-time and high-temperature blanching. A fat reduction from 5 % to 50 % has been reported for blanched potato chips or French fries [50]. In general, blanching in water solutions (calcium chloride or citric acid) instead of water, blanching under high pressure, or blanching followed by pre-drying are expected to be more efficient in the mitigation of oil uptake [12]. Regarding sensory attributes, blanching in water enhances color and textural attributes of fried products [22,122,121]. The optimal water-blanching temperature and time were found to be 85 °C and 4 min by which potato chips were highly ranked by panel tests for their crispness, color, and odor [11]. Moreira et al. [67] found out that dipping potato slices in higher concentrations of calcium chloride resulted in greater hardness and less porosity as calcium ions increased middle lamella-cell wall rigidity and thus kept cells intact during frying. Nevertheless, the higher concentrations of calcium chloride resulted in a bitter taste, a darker color, and a higher degree of shrinkage. It has been reported that potatoes blanched in organic acids solutions (citric, tartaric, or acetic acid) were less hard than unblanched ones because of starch hydrolyzation [74].

### *Pre-drying.*

Pre-drying of potato slices has been well associated with lower fat content because it both reduces initial moisture content and generates an external crust limiting oil penetration [12,50,57]. Furthermore, a combination of pre-drying and coating gums was found efficient in oil uptake reduction [57]. According to Zhang and Fan [119], prolonged pre-drying results in lower fat content which is in agreement with Asefa et al. [11] who noticed that total fat content (%) reduced from ca. 46 to 24 when pre-drying time increased from 0 to 40 min. However, Cruz et al. [21] found no significant reduction in fat content when pre-drying time increased from 10 to 30 min. In terms of sensory attributes, pre-drying resulted in harder chips in a shorter processing time than untreated ones [21]. Zhang and Fan [119] noticed a significant increase in hardness as a result of shrinkage when potato chips were dried at 60 °C. They noticed no significant change in yellowness but in L* (lightness index) and a* (redness index) color indices. On the contrary, Wu et al. [111] associated improvement in yellowness with pre-drying treatment [111].

### *Coating/edible films.*

Potato slices coated by hydrocolloids (proteins, pectin, gums, etc.) have widely been investigated. Hydrocolloids show a barrier effect against moisture loss during frying which, in consequence, leads to a reduction in oil uptake [49]. According to a review undertaken by Salehi [90], gum-based hydrocolloids decrease heat transfer coefficient and oil uptake during the deep-fat frying process. In this regard, Jafarin and Mohammadnejad [39] found that the least oil uptake was obtained when potato stripes were coated by a 2 % concentration of propolis gum. Lumanlan et al. [57] observed that xanthan gum was more efficient in the reduction of oil content than other gums (gellan, guar, and methylcellulose). An equal proportion of xanthan and basil seed gums was suggested as an efficient way of fat reduction [116]. Potato stripes coated by a solution of mucilage seed extract and ascorbic acid showed a reduction in oil uptake from 6.16 to 4.08 g/100 g [5]. Potato chips coated by alginate, arrowroot starch, and sago starch showed oil-uptake reductions by 14.56 %, 8.29 %, and 3.90 %, respectively. However, the coatings negatively affected potato chips sensory acceptance [110]. Pectin-maltodextrin coating resulted in lower fat uptake, crisper and more sensory favorable chips [66]. Transglutaminase-crosslinked whey protein/pectin films reduced oil content in French fries by 25 % [89]. A comparison was made between four different hydrocolloid solutions, namely grass pea flour protein, grass pea flour protein treated by transglutaminase, chitosan, and pectin. The least acrylamide and oil uptake was obtained for the pectin [4]. Liu et al. [53] coated potato slices by 0.2–2.2 % concentrations of sodium alginate and found that a concentration of 1.34 % resulted in the highest acrylamide reduction (ca. 77 %). Mousa [68] associated acrylamide reduction with gelling or thickening functions of hydrocolloids by which the texture of food is alerted, and thus, molecular interactions between reducing sugars and asparagine are hindered.

*Pulsed Electric Field (PEF).*

Pulsed Electric Field (PEF) is a non-thermal technology of suppling strong electrical pulses (typically by 80 kV/cm) to materials [76]. Zhang et al. [118] observed that the pulse strength was the most influential parameter in oil reduction compared to pulse number, width, frequency, and direction. The highest oil reduction (21.2 %) was obtained when the pulse strength increased by 10 kV/cm. They associated the oil reduction with resultant smooth surface and increased porosity in the cross section which allowed a higher rate of vapor to move towards the surface and so hindering oil penetration during frying. However, the application of PEF improved the texture (hardness and crispness). The authros noticed no significant effect on acrylamide formation and color. Contrary to Zhang et al. [118], Genovese et al. [30] found PEF an efficient method of acrylamide reduction. They noticed that PEF-treated potatoes contained respectively 48 % and 5.4 % less asparagine and fructose than untreated samples. Consequently, PEF resulted in acrylamide reduction of 31 % which was comparable to the 17 % acrylamide reduction achieved by water blanching. In another study, PEF was fused with either water or yeast blanching by which the highest reduction of acrylamide (58.7 %) was noticed for a combination of PEF and water blanching. Nevertheless, their fusion was not successful in oil reduction. Furthermore, the treated samples were slightly less crispy and hard compared to untreated ones; however, they were brighter and yellower in color [91]. Those findings, except the oil content, were in agreement with Zhang et al. [117] who noticed French fries were brighter and yellower in color, less hard, and having lower acrylamide content when they were pre-treated by a combination of water blanching and PEF. They reported a reduction of ca. 14 % in oil content as a result of surface gelatinization caused by blanching, as a thicker water vapor layer on the surface hindered oil penetration during frying.

*Ultrasound.*

Ultrasound is another emerging technology which can cause mechanical, physical, or chemical alterations at frequencies above 20 kHz [23]. In this context, ultrasound treatment has been associated with erosion on the surface of potato starch granules, alteration in their structure, decrease in their swelling power and solubility, increasing bound and immobilized water fractions in potato tissue, and reduction in total fat content [120]. Ultrasound at 35 kHz was found to be more efficient than 130 kHz in terms of diminishing reducing sugars and thus acrylamide reduction [6]. Movahhed and Ahmadi Chenarbon [69] reported less oil uptake when potato slices were treated at 40 kHz than 20 kHz. According to Zhang and Fan [119], ultrasound efficiency in fat reduction improved when it was combined with pre-drying treatment. Moreover, they noticed that ultrasound treated potato chips, without pre-drying, were less crispy than controls and pre-dried potato chips because ultrasound treatment degraded the structure and formed microscopic cracks. However, when ultrasound treatment was applied on pre-dried samples, crisper chips than controls were observed. In another investigation, ultrasound was coupled to PEF with the aim of improving fat content and acrylamide in potato chips. No significant reduction in fat content was noticed after the application of ultrasound; however, its fusion with PEF resulted in approximately 16 % reduction in fat content. More successfully, acrylamide content decreased ca. 66 % when combined ultrasound and PEF were applied compared to the individual applications of ultrasound (ca. 34 %) and PEF (ca. 17 %), respectively [79]. In agreement with Ostermeier et al. [79], ultrasound treated French fries did not show any significant reduction in fat content but its fusion with shellac coating (5 % concentration) decreased fat content by 57.86 % [48].

In the light of above it can be concluded that a combination of pretreatments can mostly be more efficient than their individual applications. Water blanching, for instance, is very well-known for leaching acrylamide precursors but its combination with a pre-drying treatment not only reduces acrylamide formation but also results in potato chips with less oil content and a crisper texture.

**Optimal frying conditions.**

Frying temperature and time were found to have the greatest influence on acrylamide formation which also depends on factors such as oil type, soaking, and potato variety [60]. Fig. 2 shows the effect of frying conditions on the quality attributes of potato chips. Frying temperature and time were reported to be linearly and non-linearly correlated with an increase of acrylamide, respectively [60]. At a given frying time (2 min), acrylamide levels significantly increased by raising the frying temperature from 170 °C to 190 °C [106]. An increase of both frying temperature and time induced acrylamide formation [101]. Similarly, Liyanage et al. [56] noticed the highest acrylamide level when both frying time and temperature were increased from 3 to 7 min and 160 to 190 °C, respectively. They also indicated that a shorter frying process at high temperatures is superior to a prolonged and low temperature process in the case of acrylamide degradation. However, Shojaee-Aliabadi et al. [95] found an increase in acrylamide formation even for a short frying time (3.5 min) at high temperatures (190 °C). Liu et al. [53] found optimal frying conditions to be 4.36 min and 170 °C by which sodium alginate-coated chips had the lowest acrylamide content. Regarding fat content, high temperatures speed up the crust formation which, in consequence, leads to lower oil uptake than frying at low temperatures requiring longer processing time [58]. Ghaderi et al. [31] reported ca. 35 % reduction in total fat content by increasing the frying temperature from 150 to 190 °C. According to previous studies, the extension of frying time results in higher fat content [115,123]. In this regard, the optimal frying time to minimize fat content in potato chips was found to be 3.5 min, while optimal frying temperature was either 160 or 180 °C depending on frying oil type [16]. Nevertheless, there are some reports showing no influence of frying time and temperature on the fat content [71] or increasing fat uptake with temperature increment [47]. Overall, in the case of potato chips/stripes fried to same moisture content, it can be said that the frying temperature and fat content are inversely related [43].

With regard to color, less non-enzymatic browning happens at lower frying temperatures which, in consequence, leads to brighter chips [12]. Timalsina et al. [103] associated darkness in potato chips color with an increasing of frying temperature and time. Regarding the texture, potato slices exposed to a frying process initially soften and then get harder with the progress of frying time. Initial softening is related to starch gelatinization and middle lamella solubilization, while the later hardening is because of crust generation [82]. Generally, hardness is negatively correlated with frying temperature i.e. higher frying temperature results in less hardness/crispness [43,82]. It is noteworthy that frying oil type, besides frying temperature and time, can significantly affect the quality attributes of potato chips [12,45].

Most of the previous studies, as mentioned above, have optimized a static frying process i.e. potatoes were fried under optimal constant frying temperature and time throughout the process. Nevertheless, a dynamically optimized process in which frying conditions optimally vary during the process is more advantageous [8]. Beginning the frying process of thin potato chips with high temperatures (180 °C) and then lowering the temperatures are more privileged in terms of Maillard reaction (a chemical reaction between amino acids and reducing sugars) and, therefore, acrylamide reduction [2]. In this context, a reduction of 50 % in plantain acrylamide occurred when the initial frying temperature of 180 °C rapidly decreased to 140 °C [15]. Arias-Mendez et al. [8] designed a dynamic optimized potato frying process with the objective of minimizing acrylamide whilst keeping color and texture desirable. A two-zone optimal temperature at a constant frying time resulted in up to 16.5 % less acrylamide than a constant frying time and temperature. More reduction in acrylamide was obtained when the temperature was split in five zones with different frying times at each zone. The optimal design was found to be short amount of frying at a high temperature in the beginning followed by a gradual decrease of temperature. Even though dynamic control has been found to be superior to a static frying process, there are few scientific reports in this regard, and thus, further studies are still needed to dynamically optimize acrylamide, fat content, and sensory attributes.

**Machine vision application.**

Machine vision, including hyperspectral imaging/spectroscopy and color cameras (Table 2), has been gaining popularity in potato processing. Hyperspectral Imaging (HSI) provides spatial information over a wide spectral range. However, it suffers from being computationally intensive and high cost. Compared to HSI, a color camera is more affordable in terms of processing time and cost. In the following, a summary is given of the applications of HSI and color cameras in the quality inspection of potatoes prior and post processing.

*Quality inspection of raw potatoes.*

The prediction of dry matter content and starch has been the topic of study of many researchers because they are among the critical parameters that should be considered before the application of potato tubers to any further process. In this sense, spectral data of 35 varieties of potatoes were acquired in a waveband of 1100–2000 nm. The spectral data was correlated to the dry matter content by developing Modified Partial Least Square (MPLS) models. MPLS models were capable of accurately predicting the dry matter content with RMSE = 4.29 % [27]. In another study, Fourier-transform near-infrared spectrometry (FT-NIR) was used to predict the dry matter content of three potato varieties [17]. The spectral data (800–2500 nm) was acquired from unpeeled, peeled, and sliced tubers. The models best predicted the dry matter content (R-squared = 0.83 and RMSE = 1.23 %) for the case of peeled potatoes which indicates the negative interference of skin in the light-object interaction. There are further studies confirming the potential of NIR spectroscopy in the prediction of dry matter content in potatoes [34,98]. Even though dry matter can be a good indicator to pre-sort potatoes in such a way that those of low dry matter content are not further processed, more factors such as proportion of starch to reducing sugars, for instance, must be considered to come to a better decision. In this sense, HSI (382–1004 nm) in conjunction with Partial Least Square Regression (PLSR) was used to predict starch content in freshly-cut potato slices [109]. The results showed that a subset of optimal wavelengths could predict starch content with high accuracy (R-squared = 0.94 and RMSE = 1.63 %). Farhadi et al. [28] developed PLSR models using the spectral data of potatoes taken in the range of 450–1000 nm. They reported R-squared and RMSE values in the ranges of 0.958–0.974 and 0.134–0.333 % for the prediction of starch content, respectively. The potential of HSI in the prediction of starch content was sought by Kjær et al. [46]. They collected the spectral data (380–925 nm) from both intact potato tubers and cylinders removed from the center part of tubers. The results showed higher R-squared values (0.66–0.71) in the case of intact tubers than those of cylinders (R-squared = 0.31–0.42). They also found that predictions by HSI were more accurate than those of Dielectric and Nuclear Magnetic Resonance techniques. The potential of HSI (400–1700 nm) was sought in the prediction of amylose and amylopectin. When the full spectrum ranging from 400 to 1000 nm was introduced as inputs of Cascade Forest models, amylopectin and amylose contents were predicted with R-squared = 0.8517 and RMSE = 1.1578 %, and R-squared = 0.9662 and RMSE = 0.7882 %, respectively. The prediction accuracies of amylopectin (R-squared = 0.9658 and RMSE = 0.7761 %) and amylose (R-squared = 0.9731 and RMSE = 0.6908 %) improved when the models were developed using the wavebands of 900–1700 nm [35]. Besides starch content, NIR imaging/spectroscopy has widely been investigated to predict reducing sugars. Rady et al. [86] fused HSI (400–1000 nm) with NIR spectroscopy to predict sugar content in potato tubers. The NIR spectroscopy data collection was carried out in two modes of reflectance (900–1685 nm) and interactance (446–1125 nm). The best prediction result for glucose (r = 0.94 and RMSE = 0.0182 %) was obtained for a fusion of HSI and the interactance mode, whilst sucrose was best predicted (r = 84.4 and RMSE = 0.0354 %) when the interactance and reflectance modes were combined. According to Camps and Camps [17], the prediction accuracy of reducing sugars was dependent on genotype such that R-squared values ranging from 0.63 to 0.84 were obtained for potato varieties of Lady Claire, Markies, and Innovator. Shao et al. [93] took images of sweet potatoes in a spectral range of 400–1000 nm. Support Vector Regression models (SVR) were developed using a subset of optimal wavelengths. SVR models could best predict soluble solids content with an accuracy of R-squared = 0.8581 and RMSE = 0.2951 %. Asparagine prediction, as an acrylamide precursor, has been another topic of interest. Ayvaz et al. [13] collected spectral information of potatoes in the range of 4000–700 $cm^{-1}$. They used the range of 1800–1299 $cm^{-1}$ for developing PLSR models by which asparagine was predicted with R-squared and standard error of 0.95 and 0.15 mg/g, respectively. In another study, hyperspectral images taken in the range of 380–925 nm were fused with PLSR by which R-squared values of = 0.70 and 0.54 were obtained for prediction of asparagine in intact and sliced tubers, respectively [46]. The potential of HSI in prediction of pectin has recently been investigated. In this matter, Yang et al. [114] used two HSI systems in the spectral ranges of 400–1000 nm and 900–1700 nm to non-destructively predict total soluble pectin (TSP), dilute alkali soluble pectin (DASP), water soluble pectin (WSP), and chelator soluble pectin (CSP) in intact mulberry fruit. The best prediction results were achieved for TSP (R-squared = 0.755 and RMSE = 7.117 g/kg) and DASP (R-squared = 0.691 RMSE = 15.037 g/kg); the models failed at estimation of WSP and CSP. In another study, HSI systems A (380–1030 nm) and B (874–1734 nm) in conjunction with PLSR and Least Squares Support Vector Machine (LS-SVM) models were employed to predict protopectin, WSP, and TSP. The prediction accuracy for protopectin (R-squared = 0.811 and RMSE = 0.246 mg/g) was higher than those of WSP (R-squared = 0.537 and RMSE = 0.392 mg/g) and total pectin (R-squared = 0.711 and RMSE = 0.418 mg/g), [125]. Most recently, Huang et al. [36] suggested a fusion of infrared microspectroscopy with confocal Raman and stimulated Raman scattering microscopy as a promising tool to visualize spatial changes in the cell-wall polysaccharides of peach fruits. Besides chemical components, NIR spectroscopy was applied to predict the texture (RMSE = 1.33 kg $cm^{-2}$) and yellowness (RMSE = 8.96) of potato flesh [27]. Xiao et al. [112] concluded that HSI is an efficient way of explaining L*, a*, and b* indices (R-squared >= 0.84).

*Quality inspection of fried potatoes*

Acrylamide prediction was investigated by taking its spectral information in NIR (1100–2500 nm) and mid-infrared (MIR = 4000–8000 nm) regions. Even though acrylamide prediction was more accurate in the NIR region (r = 0.95 and standard error = 145 ppb) than that of MIR (r = 0.79 and standard error = 215 ppb), the prediction accuracy in the NIR region could have been influenced by fat and starch content changes but that of MIR was more dependent on acrylamide [33]. To reduce the influence of fat content, potato chips were pressed to force the oil out. The samples were then applied to a FT-IR spectrometer working in

4000–700 $cm^{-1}$. The acrylamide was best explained by the spectral region of 1699–1201 $cm^{-1}$. The corresponding prediction correlation coefficients and standard errors were found to be 0.93–0.98 and 75–98 μg/kg, respectively [87]. Adedipe et al. [3] reported NIR spectroscopy (400–2500 nm) as an efficient way of acrylamide prediction (R-squared = 0.98 and standard error = 135 μg/kg).

Instead of direct prediction of acrylamide using spectroscopic methods, many researchers related color changes to acrylamide; the more browning, the higher acrylamide [61,113]. Convolutional Neural Networks (CNN) trained on color images successfully classified acrylamide containing chips with accuracies above 90 % [9,63]. With regard to fat content, three MIR regions of 920–500, 1800–1060, and 3040–2700 $cm^{-1}$ were selected to build PLSR models upon. The spectra taken in Singular Reflectance mode resulted in lower relative standard errors (RSE) of 1.24 % than Diffuse Reflectance (RSE = 1.85 %). Furthermore, the NIR wavebands of 4380–4130 and 6300–5300 $cm^{-1}$ predicted fat content with RSE = 1.86 % which was comparable to that of the diffuse reflectance in MIR [64]. Further studies in comparison of NIR (10000–4000 $cm^{-1}$) and MIR (4000–700 $cm^{-1}$) for fat prediction showed that they were both accurate by which r greater than 0.96 and standard error less than 1.6 % were achieved [94]. Pedreschi et al. [83] reported accurate prediction results (r = 0.99 and RMSE = 0.99 %) for fat content in potato chips when NIR information (460–1040 nm) was fused with PLSR. The potential of NIR spectroscopy (800–2500 nm) in the prediction of fat content (r = 0.996 and RMSE = 0.211 %) was later duplicated by [75]. Regarding color and texture, a color camera was used to classify balanced and unbalanced potato chips fried at 120, 150, and 180 °C with regard to their texture and color attributes. From each color image, more than 1500 features were extracted among which 11 features were singled out. Classification algorithms build upon the optimal features resulted in an accuracy of ≥ 90 % in all conditions [81]. Romani et al. [88] well correlated color indices measured by a flatbed scanner and colorimeter (R-squared greater than 0.962) by which they were able to map normal, browning, and oily areas over a potato chips disk. The superiority of texture-based image features to color ones was reported when it was aimed to discretize potato chips according to their appearance [65].

The contactless and nondestructive nature of optical sensors in combination with the potential for continuous and real-time measurement of key information within a product are a prerequisite for the realization of the intelligent dynamic control of the frying process based on key characteristics of the product and its changed. However, to reach the full potential of process understanding and (individualized) process control in which frying conditions are optimally tuned with respect to the raw-materials' and products' characteristics and their frying behavior (including "product-process interactions") so that potato chips with optimum quality are produced while resource and process efficiency are optimized the development of a fully-fledged Digital Twin is key. According to Grieves [32], in the development of digital twins three general stages can be classified: 1) digital models of varying degrees of accuracy, which are virtual representations of a procudt or physical system, they can physics based or data driven and in some cases a combination of the two (hybrid models); however, there is no automated data exchange between the physical and the digital sphere; 2) digital shadows which usually are elaborate digital models which incorpotate an automated upload of information from the real world object to the virtual one; the digital shadow is primarily an instrument to transfer the real world into the digital one and could be used for e.g. decision support; 3) digital twins enable bidirectional information flow in real-time between the physical and digital sphere; they aim to use simulations and (process) models to generate an image that is as accurate as possible and can e.g. be used for predictive adaptive process control with a view to product quality optimization. Jones et al. [40] give an extensive overview of the state of the art in DT development and the still existing gaps. These include but are not limited to 1) a still general great lack of knowledge of product and process related characteristics and indicators as well as their interactions, 2) a great development need for sensors and sensor networks to capture central indicators, 3) the need for the development of hybrid modelling approaches including reliable artificial intelligence aspects; 4) challenges in the technical implementation of DTs as current technologies used were not developed with DTs and the associated data streams in mind; 5) the integration of virtual entities and environments is not solved satisfactorily and 6) natural produce such as potatoes are very heterogeneous in their nature, thus making the development of DTs more complex than e.g. in technical products or in building related projects.

**Smart frying design.**

Recent progress in optical components, image processing, learning and optimization algorithms, control systems, Internet of Things (IoT), along with emerging techniques in foodstuff frying field has made the appearance of intelligent fryers imminent. In an intelligent process, end-product attributes are guaranteed by both providing raw commodities meeting the critical requirements and dynamic control of frying conditions. To determine the best dynamic control design, it is of high importance to actively integrate commodity characteristics in all considerations. In other words, the integration of the product into the overall system DT will help dynamic optimization algorithms to find the best frying conditions under which desired quality attributes are fulfilled. Fig. 3 depicts a schematic of a smart frying system which is discussed in the following.

Step A.

In this step, potato tubers are inspected for their external characteristics such as size, shape, sprouting, skin appearance, eyes, and other defects. In the case of potato chips, processors are most interested in round-oval potatoes with medium size (40 to 75 mm) to minimize peeling loss [51,105]. The sorting system consists of a 3D camera, illumination sources, and sorting actuators. The 3D camera provides both color and depth information. Its potential in measuring tubers size, volume, bumps, and hallows has already been reported by [96]. The illumination can be provided by white LEDs as they can generate light in the visible range (blue to red), are easy to control, energy efficient, and produce less heat compared to halogen lamps. The images of tubers are consecutively captured and clouded to the control unit (Fig. 3-b). The control unit includes image processing algorithms, learning algorithms, mathematical models, dynamic optimization algorithms, control layers e.g. proportional-integrative-derivate (PID) or model reference adaptive (MRAC) control mechanisms or an approach including Markov-Chains to control the frying temperature, and controller programs to control imaging units and actuators. In the control unit, images are processed to detect Region of Interest (ROI), extract color and morphology features. The information is fed into learning algorithms to classify the tubers. Thereafter, the output is fed to the controller programs to command the actuators to only proceed those tubers to step B which are intact and uniform in size and shape.

Step B.

In step B, internal quality attributes are measured to make appropriate decisions upon. These include dry matter content, reducing sugars, asparagine, starch, and textural properties to name but a few. According to Table 3, the spectral region between 750 and 1900 nm can be sufficiently informative and reliable to predict the quality attributes of interest. The information can be collected by either spectrometers or imaging devices. Spectrometers are more affordable and fast processors; however, they collect information from few points compared to imaging devices which scan the whole area. The spectral data is then clouded to the control unit (Fig. 3-b) where the relevant information is extracted and fed into prediction algorithms, e.g., Convolutional Neural Networks, to estimate the aforementioned quality attributes. Accordingly, the control unit will command the corresponding actuators to sort potato tubers in relevance to their quality attributes; potato tubers contain more than 2 % of reducing sugars, for instance, must not be further

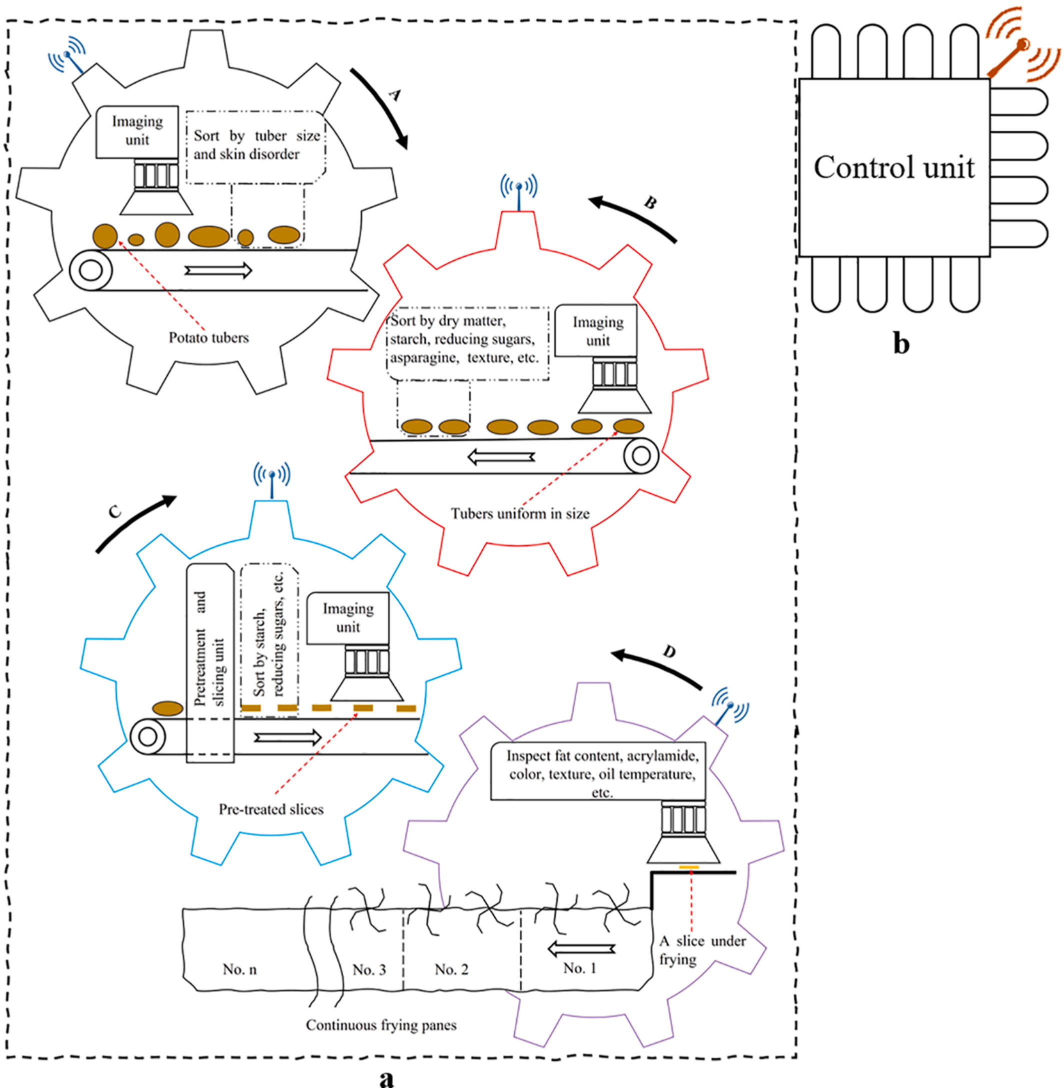


**Fig. 3.** Schematic of intelligent frying process of potato: a) frying chain, b) control unit.

processed because they are acrylamide precursor [105].

Step C.

Based on the physiochemical attributes of intact tubers, the smart system decides which pretreatment should be applied. For instance, if potato tubers contain high amounts of reducing sugars, the potato tubers are better to go through a blanching treatment to leach the sugars out. This can be followed by the application of pre-drying to remove extra water. If tubers are less firm, for instance, pre-drying or coating films could enhance the texture. However, further research is still needed to answer the question of which pre-treatments would be most efficient given the initial composition of tubers and the fluctuations thereof. The slices are then gone through the pealing and cutting operations. Afterwards, the slices are carried by a conveyor towards the frying pans. Given the non-uniform distribution of chemical components over a tuber, there will be a monitoring system above the conveyor to scan and sort slices according to their physiochemical quality attributes. In addition, the size of slices can also be taken into consideration in the sorting process. From this point of view, each frying pan could be provided with a batch of slices uniform in size and physiochemical attributes. The monitoring system is equipped with either a hyperspectral or multispectral sensor, working at optimal wavelengths (Table 3), in conjunction with learning algorithms to predict dry matter content, total starch content, amylose, amylopectin, phosphorus, acrylamide precursors, pectin, color, and texture properties for each slice. This comprehensive information will be fed into predictive algorithms to estimate the frying temperature and time trajectories in advance for each batch of slices. The predictive algorithms will also estimate the quality attributes (color, crispness, fat content, moisture content, and acrylamide) at the end of process.

Step D.

In this step, each batch of slices will be transferred to a series of frying pans. Each pan is initially set to the optimal frying temperature already estimated by the predictive algorithms in step C. The system comprises two monitoring systems. One monitors the frying oil temperature and quality. The quality degradation of frying oil can be inspected by a NIR spectrometer to come to a decision about its replacement time [54,77]. The other monitoring system includes an imaging platform equipped with a hyperspectral/multispectral sensor. Given Table 3, an optical sensor covering the spectral range of 400–2500 nm would suffice. The monitoring process can be done in this way that some slices will be removed, in pre-defined intervals, from the frying pan to the imaging platform. Their images will be clouded to the control unit (Fig. 3-b) to estimate acrylamide, fat content, color, moisture content, and crispness. The predicted attributes will be used to update the parameters of frying kinetic models. Afterwards, the models will be solved by dynamic optimization algorithms to correct the frying time trajectory already estimated in step C. When the processing time in each stage is reached, the control program (Fig. 3-b) will command the

**Table 3**
Spectral bands related to the quality attributes of raw and processed potatoes.

| Chemical component | Optimal wavelengths (nm) | Reference |
|---|---|---|
| Dry matter content | 1060–1330 and 1640–1830 | Camps and Camps [17] |
| | 750–950 | Subedi and Walsh [98] |
| | 1024, 1068, 1135, 1208, 1252, 1403, 1460, and 1641 | Su and Sun [97] |
| Starch | 386, 389, 392, 395, 403, 406, 425, 485, 864, 914, 915, 927, 964 | Wang et al. [109] |
| | 1018, 1064, 1115, 1202, 1319, 1366, 1517, and 1628 | Su and Sun [97] |
| Reducing sugars | 1065, 1335, 1635, and 1835 | Camps and Camps [17] |
| | 670, 710, 798, 830, and 888 | CHEN et al. [19] |
| Asparagine and glutamine | ≈5936, ≈6146, ≈7137, and ≈7434 | Ayvaz et al. [13] |
| | 380–925 | Kjær et al. [46] |
| Acrylamide | 400–700, 942–1084 with a peak at 994, and 1900–2200 with a peak at 1930 | Adedipe et al. [3] |
| Fat | 920 | Pedreschi et al. [83] |
| | ≈1678, ≈1734, ≈2225, ≈2350, ≈2434, ≈3345, ≈3429, ≈3511, ≈5727, ≈6798, ≈7163, and ≈7251 | Shiroma and Rodriguez-Saona [94] |
| | 1392, 1726, and 1780, 2084, and 2175 | Ni et al. [75] |

paddles to move the slices to the next frying pan.

In a further development step, after collection of extensive data from the above process, a fully-fledged DT can be realized using the information on dynamic changes of the product within the process.

## Conclusion

This paper presents a novel approach for the realization of a smart potato frying process which combines crucial information on product quality with the control of the process itself. It outlines the development needs and argues that only if the interactions between the product and the technological system are sufficiently understood optimal system performance and highest product quality can be achieved. The authors further argue that to reach this goal the development of fully fledged digital twins (DT) and their combination is of utmost importance. Furthermore, for the realization of a fully fledged DT the development of hybrid models combining physics based models with data driven ones (statistical and/or artificial intelligence) is crucial as only then the true dynamics of the impact of the process on the product can be fully understood and utilized for optimum process design and control. To provide the data necessary for the development of the hybrid models and also for process control, vast quantities of data on the product characteristics need to be collected, thus making further investigations on the use of non-invasive visual sensors for product quality inspection central. Decision making and control algorithms need to be developed for pre-sorting of raw-material, pre-treatment based on product characteristics and control of the frying process also based on product characteristics.

This approach is clearly set apart from earlier studies which either focused on chemometrially combining product characteristics with computer vision applications or optimizing the frying conditions and pre-treatment technologies. This previous lack of integrative work is perhaps because it is a multidisciplinary topic which requires knowledge of food science and engineering, computer vision, process engineering, dynamic optimization, and controls.

The authors expect that the developed approach can, with moderate modification, be transferred to other food processes such as drying.

Future work should include the integration of considerations into energy and resource efficiency as well as sustainability aspects such as waste reduction.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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