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# Texture and *in vitro* starch digestion kinetics of French fries produced from potatoes (*Solanum tuberosum* L.) pre-treated with pulsed electric fields

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ABSTRACT

The impact of Pulsed Electric Field (PEF) processing pre-treatment on the texture and kinetics of *in vitro* starch digestibility of French fries made from two potato cultivars (*Solanum tuberosum* L.) containing dry matter content ranging from 19 to 22% was investigated. Whole and steam-peeled potato tubers were treated with a pilot scale PEF unit (electric field strength of 1.1 and 1.9 kV/cm with energy input <10 kJ/kg or ~50 kJ/kg). This trial was carried out in a commercial French-fry plant using an industrial scale cutter, blancher, fryer and blast-freezer to prepare the frozen par-fried French fry samples. After subsequent final batch frying of the frozen fries, at 180 °C for 3 min to mimic the typical preparation practice at restaurant, retail and household, the outer crust of the fries produced from PEF-treated potatoes was significantly harder (9.4–16.3 N) than crust produced from untreated potatoes (6.9–8.5 N). High intensity (1.9 kV/cm with energy input ~50 kJ/kg) PEF processing was found to cause defects (*i.e.* hollowness in the internal core) in the fries. A fractional conversion model was a good fit for the starch digestion kinetics of all French fry samples during the small intestinal phase (based on standardised INFOGEST static *in vitro* digestion assay). A lower % of total starch hydrolysis was predicted for French fries produced from high dry matter (>21%) tubers pretreated with PEF at electric field strength of 1.9 kV/cm. The findings generated in this study demonstrate PEF pretreatment may influence the texture of French fries and the extent of starch digestion that occurs.

## 1. Introduction

The production of French fries involves a carefully controlled multistep processing operation to transform raw potatoes into fries with a crispy crust and a golden-brown colour. The industrial production of par-fried and frozen French fries involves the following processing steps: washing, peeling, preheating, cutting, blanching, drying, par-frying and blast freezing (Fig. 1**a**) (Vinci et al., 2011). The production of French fries is an energy and water intensive process (Walker et al., 2018) and the adoption of emerging technologies such as pulsed electric fields (PEF) can help reduce processing costs and improve the efficiency of water and energy use (Botero-Uribe et al., 2017). PEF technology is based on the application of high voltage short electrical pulses to a food product placed between two electrodes. PEF processing increases the permeability cell membrane which consequently softens the potato texture (Angersbach et al., 2000). The inclusion of a PEF processing step into an industrial French fries process line has been proven to be the most beneficial if the PEF unit is located prior to the whole potatoes being cut into stick form (Fauster et al., 2018; Heinz & Toepfl, 2022) (Fig. 1**b-c**). In this configuration PEF processing effectively replaces the preheater step and achieves a similar impact in softening the potato texture to facilitate the cutting process and reducing the breaking and feathering loss of potatoes (Fauster et al., 2018). Importantly the replacement of the preheater step by PEF processing reduces the process time, water use and energy consumption (Hill et al., 2022). Moreover, PEF has been shown in multiple studies on potato tuber, at laboratory scale, to reduce oil uptake during frying (Ignat et al., 2015; Janositz et al., 2011; Zhang, Lyu et al., 2021), reduce browning (Genovese et al., 2019; Ignat et al., 2015; Ostermeier et al., 2021; Zhang, Lyu et al., 2021; Zhang et al., 2022) and significantly change the textural properties of fried potato samples in the form of cubes, slices, crisps, strips or sticks (Genovese et al., 2019; Zhang, Lyu et al., 2021a; Zhang et al., 2022, Zhang, Zhao et al., 2021).

To date, the work of Fauster et al. (2018) is the only published validated study that provides valuable baseline information on the process performance of PEF technology in the industrial scale production of French fries. However, the work of Fauster et al. (2018) only con-

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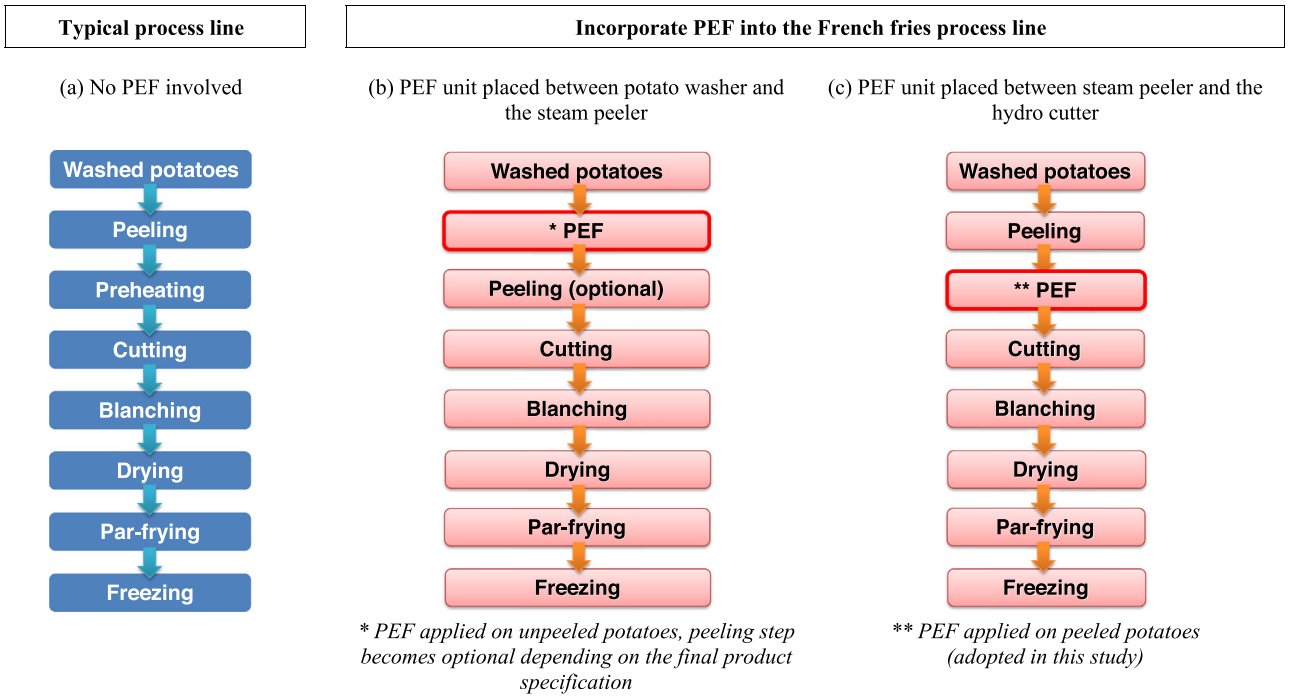


**Fig. 1.** Simplified diagrams illustrating (a) the existing process line in a commercial French fries production plant and (b-c) how PEF technology can be incorporated into the process line.

sidered the use of PEF on whole unpeeled potatoes (Fig. 1**b**) and it is known that the presence of the skin greatly limits the effectiveness of PEF (Faridnia et al., 2015). This point is important as peeling is an integral part of the production process for the majority of French fries (Somsen et al., 2004). Therefore, to add more industrial relevant insights the use of PEF processing on whole peeled potatoes (Fig. 1**c**) during the commercial production of French fries needs to be investigated.

Potatoes contain complex carbohydrate known as starch, which makes up most of the tuber total dry matter (DM), between 60 and 80% (Kita, 2002). In industrial applications, determination of DM content (or specific gravity) prior to processing is vital as DM serves as a potato grading index and as an indicator of the yield and the quality of fried French fries such as texture and colour (Schippers, 1976; USDA, 1969). Starch is comprised of glucose units linked together by glycosidic bonds in the form of either amylose or amylopectin. Upon consumption, starch is hydrolysed by amylase into smaller polysaccharide fragments and oligosaccharides and eventually broken down to smaller glucose units in the small intestinal. Starch can be classified according to the rate of glucose release during gastrointestinal condition: rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) (Englyst et al., 1996). RDS causes a rapid increase in the blood glucose level after digestion, SDS is digested at a slower rate, and RS is the remaining starch unable to be digested in the small intestine. Apart from the genotype difference in potatoes, food processing plays an important role influencing the starch in the potatoes, its subsequent digestion and the corresponding glycaemic response (García-Alonso & Goñi, 2000; Nayak et al., 2014; Singh et al., 2020). As the consumption of French fries is popular in domestic households (Mesias et al., 2020) and food service establishments (Mesias et al., 2019), the long-term consumption of any potato products has been linked to health problems such as cardio-metabolic diseases (So et al., 2020), type 2 diabetes (Bidel et al., 2018) and hypertension (Huang et al., 2019). Therefore, careful consideration of the potential nutritional and health aspect that the incorporation of PEF processing into commercial French fries manufacturing is required. In this context, PEF has been demonstrated to increase the SDS content of native potato starch (Li, Wu et al., 2019) and potato crisps produced using PEF-treated potatoes induced more satiation (Cahayadi et al., 2020). These findings strongly suggested that PEF has the potential to slow down the digestion rate of potato starch. However, the impact of PEF on the starch digestion profile of French fries (*i.e.* a deep-fried potato product) has not been reported.

The objective of this study was to evaluate the kinetic behaviour of *in vitro* small intestinal starch digestibility of French fries produced in an industrial scale production environment using potatoes PEF pre-treated at different electric field strengths and specific energy inputs. In this study, an industrial scale cutter, blancher, fryer, and blast-freezer were used to prepare the French fries and two potato cultivars with different DM contents were used.

## 2. Materials and methods

### 2.1. French fries production

#### 2.1.1. Potato tubers

Two potato varieties (*Solanum tuberosum* L.) were used in this study. One potato variety had dry matter (DM) less than 20% which is referred to as “Moderate DM” and the other potato variety had DM greater than 21% which is referred to as “High DM”. The dry matter (DM) content of potatoes was determined on-site prior to processing based on specific gravity measurement, *i.e.* the ratio of weight in air and (weight in air minus weight in water). All tubers were stored post-harvest (covered with a heavy layer of soil) according to their optimum storage condition (controlled temperature of 10 °C and relative humidity of ≥90%) in a commercial potato storage room. The potatoes used in this trial had been stored for no longer than 3 months.

#### 2.1.2. French fries production and PEF treatment

The industrial production of French fries generally involves potato washing, peeling, preheating, cutting, blanching, drying, par-frying, and blast-freezing steps. In this study, a pilot scale PEF unit (Elea GmbH, Quakenbrueck, Germany), equipped with a 30-kW pulse generator (HVP30) and a treatment bath fitted with an electrode and conveyor belt, was located between the steam peeling and cutting steps in the processing line (as illustrated in Fig. 1**c**) and replaced the existing preheater

step. The HVP30 generator transmitted the high voltage pulses (up to 30 kV) to the treatment electrode (stainless steel, positioned in parallel with an electrode gap of 130 mm) fitted inside the treatment bath. When the potato tubers entered the processing plant, they were stone-washed and steam-peeled. Then, the peeled potatoes were dropped into the feed of the treatment bath filled with carrier water (conductivity ranged between 900 and 1100 μS/cm) and were conveyed pass the PEF electrode. Peeled potatoes were PEF-treated with varying intensities of electric field strength and total energy input in this study, which resulted in four different process parameters. "PEF A" and "PEF C" involved the application of total energy input averaged at 2 and 50 kJ/kg respectively, with a fixed electric field strength at 1.1 kV/cm. "PEF B" and "PEF D" involved the application of total energy input averaged at 7 and 50 kJ/kg respectively, with a fixed electric field strength at 1.9 kV/cm. For all the four process parameters tested, rectangular pulses with a pulse width of 20 μs and pulse frequency of 200 Hz were applied. These four PEF process parameters were tested on each potato cultivar in one production day, but the experiment was conducted on separate days (*i.e.* 1 week apart) for different potato cultivars.

After PEF processing the treated potatoes were transported to the hydro-cutter to be cut into fries with an edge length of 7 mm. The potato fries then entered a 2-stage continuous blancher (ranged between 74 and 82 °C for 8 to 10 min depending on the potato cultivar and their quality properties when entering the processing plant). Afterwards, the blanched fries travelled on a flume system and entered the hot-air dryer via belt conveyor (average temperature of 35 °C for no longer than 12 min). Finally, the fries were par fried in a continuous industrial fryer (average temperature of 185 °C for 50 s and 9 cm oil depth), frozen at −20 °C on a conveyor belt for at least 18 min and then packaged into 1 kg bags.

It took approximately 45 to 60 min for the peeled potatoes treated with one PEF process parameter to be transformed into French fries on a process line operating at a capacity of 20 tonnes/hour, and then packaged. Therefore, each PEF process parameter was conducted successively in this study, on an hourly basis, in the industrial environment within the same day. The entire steps were repeated for the second PEF process parameter in the next hour with independent batch of potatoes entering the processing plant. For every PEF process parameter tested, untreated potatoes without receiving any PEF treatment (thereafter known as "No PEF" samples) were sampled after steam peeling and then proceeded to the remaining French fries production line together with PEF-treated potatoes. In other words, a set of "No PEF" samples were obtained in every PEF process parameter, resulting in a total of 4 set of "No PEF" samples in this experiment. The untreated and PEF-treated potatoes were processed into French fries under similar condition as outlined earlier, in industrial environment, and they were differentiated on the process line (during blanching and drying) by placing them into separate zipped nylon mesh bags. When the fries were about to enter the continuous fryer, they were transferred into separate stainless-steel perforated cages capable of withstanding the high temperature of frying oil. After par-frying, the fries were transferred again into the zipped nylon mesh bags and returned to the process line for blast freezing. After freezing and packaging, the samples were stored at −20 °C and transported to the Department of Food Science (Dunedin, New Zealand) for analysis. The use of mesh bags and stainless-steel cages to differentiate French fries produced from untreated and PEF-treated potatoes on the industrial process line in this study has been demonstrated in our preliminary experiment to have negligible influence on the quality of fries (*i.e.* colour after finished frying).

### 2.2. Crust hardness of French fries produced from untreated and PEF-treated potatoes

French fries served to customers are typically produced through a two-stage frying process consisting of par frying and finish frying with intermediate freezing and frozen storage in between them (Millin et al., 2016). In this study, all the French fries were par-fried and frozen at the processing plant, followed by a second frying step (*i.e.* finish frying) at the laboratory prior to determining their crust hardness. Before frying, the frozen par-fried French fries were sorted according to their length (short <50 mm, medium and long >100 mm) based on the work of Van Loon et al. (2007). Medium length fries (between 50 and 100 mm depending on the potato cultivar) were randomly selected and then equilibrated at −20 °C (Irinox MultiFresh 45, Treviso, Italy) for at least 1 h to ensure all fries had similar initial temperature before frying. The frozen fries (300 g) were fried in canola oil (Smart Choice, New Zealand) at 180 ± 3 °C for 3 min in an electric deep fryer (Blue Seal Evolution series E44E, Moffat, Auckland, New Zealand). When the fries were removed from the fryer, they were placed on a cooling rack to allow excess oil to drip off.

Texture analysis of the French fries was conducted within 10 min of finish frying to prevent moisture absorption from the surrounding air and moisture loss from the inner fries to the crust, which would make the fries soggy and limp. The maximum cutting force through each fry was measured using a texture analyser (TA.HDplus, Stable Micro Systems, Surrey, England). A blade set was installed on the texture analyser which consisted of a Warner Bratzler cutting blade with guillotine edge (HDP/BS, 90 mm height, 70 mm width, 3 mm thickness), blade holder, a slotted blade inserts and a heavy-duty platform. The operating parameters for the crust hardness measurement were: 5 kg load, 2 mm/s pre-test and test speed, 10 mm/s post-test speed, 5 *g* trigger force, and 10–15 mm cutting distance. Each fry was placed in the centre of the slotted blade insert and the cutting blade was set to 10 mm above the fry to completely cut the fry transversely. Cutting test with guillotine blade probe was recommended by Li et al. (2020) to better correlate the instrumental parameters with the sensory attribute hardness for French fries. The maximum peak force for the first peak from the force (N) *vs.* cutting distance (mm) curve represents the crust hardness of French fries (Sadeghi et al., 2021). Duplicate texture measurements were taken for each fry (*i.e.* at 2 different positions on the same fry, approximately 10–15 mm away from both ends) and a total of 10 fries were measured from each type of French fries sample. In total, 20 texture measurements were conducted for each PEF processing condition. After the texture measurement, the appearance of the inner core of the remaining cut fries were captured using a digital camera, and images were saved in .jpeg format.

### 2.3. *Simulated* in vitro *human gastrointestinal digestion procedure*

The starch digestibility of French fries produced from PEF-treated and untreated potatoes was determined using a standardised INFOGEST static *in vitro* digestion method (Brodkorb et al., 2019) to simulate the oral, gastric and small intestine digestion in human body. Three simulated fluid stock solutions during the different stages of the digestion: simulated salivary fluid (SSF, containing 2 mM sodium chloride and 25 mM potassium chloride, adjusted to pH 7), simulated gastric fluid (SGF, containing 1 mM hydrochloric acid, 151 mM sodium chloride and 20 mM potassium chloride, adjusted to pH 3) and simulated intestinal fluid (SIF, containing 100 mM sodium bicarbonate, adjusted to pH 7) were prepared and the relevant digestive enzymes were added to each solution on the day of experiment.

The *in vitro* simulation of digestion was performed in 50 mL digestion vessels (Schott flat bottom glass bottles, Mainz, Germany) inside a 37 °C temperature-controlled incubator (LabServ, Overlay 26, Hutt City, New Zealand) with continuous shaking motion of 55 strokes/min (DLAB, SK-R1807-S, California, USA). The digestion procedure was initiated by addition of 8 mL of SSF into finely ground French fry samples (5 g), followed by incubation and shaking for 5 min. Afterwards, 2 mL of α-amylase (75 U/mL digest, purified from *Aspergillus oryzae*, Sigma 10,065) was added to mimic oral digestion and the digest mixture was returned to the incubator for 5 min with shaking. The pH of the digest was adjusted to pH 3 with 1 M HCl to inactivate the α-amylase.

Once the pH was reached, 8 mL of SGF (added with porcine pepsin (AppliChem A4289)), followed by incubation at 37 °C and shaking for a total of 120 min to simulate the gastric digestion. Then, the pH of the digest was adjusted to pH 7 with 1 M NaOH to inactivate the pepsin. To simulate the small intestinal phase, 16 mL of SIF (added with porcine pancreas pancreatin (Sigma P1750) and porcine bile extract (ChemCruz SC-214,601)) was added and then incubated for another 240 min with shaking. French fries were subjected to the simulated *in vitro* digestion procedure (up to 6 h long from oral to gastric and small intestinal) in triplicate. A similar digestion assay was conducted on French fries for up to 6 h without the addition of amylase, pepsin, pancreatin and bile extract into the SSF, SGF and SIF solutions respectively. This was to ensure that the amount of digested starch observed in this study was solely attributed by the enzymatic action of the digestive enzymes added and not because of the pH difference during the gastrointestinal process.

### 2.4. *Kinetic study on the* in vitro *starch digestion of French fries at small intestinal phase*

In this study, the kinetics of starch digestion in the small intestinal phase was investigated. A small amount of starch (<10%) was digested prior to small intestinal phase (*i.e.* at oral and gastric phases) but the reaction proceeds slowly and hence was excluded from the kinetic study. During the subsequent 4 h-long small intestinal simulation phase (*i.e.* after the addition of SSF, SGF and SIF) at 0, 20, 60, 90, 120, 180 and 240 min after the addition of pancreatin containing a mixture of trypsin, amylase and lipase, ribonuclease, and protease, 0.5 mL of digest was removed from the digestion vessel. At the end of each predetermined time point, the enzymatic hydrolysis in each 0.5 mL digest was immediately stopped by a heat shock treatment at 100 °C for 10 min in a water bath. Then, 2.5 mL of deionised water was added to each digest sample and centrifuged at 2475 *g* for 10 min to collect the digestive supernatant for D-glucose analysis.

#### 2.4.1. *Determination of digested starch as a function of digestion time*

The degree of starch breakdown to glucose as a function of digestion time during the small intestinal phase was quantified using the Megazyme D-glucose assay kit (K-GLUC: GOPOD format) (Wicklow, Ireland). Fifty microliters of amyloglucosidase (3300 U/mL purified from *Aspergillus niger*, Megazyme) was added to each digestive supernatant and mixed well to ensure the starch hydrolysed by digestive enzymes during simulated *in vitro* digestion was converted into D-glucose form. The digestive supernatants were then incubated in a water bath at 50 °C for 60 min with intermittent mixing for every 15 min. Subsequently, the digestive supernatant was diluted with deionised water to a final volume of 10 mL. The mixture (50 μL) was then reacted with 1.5 mL of glucose peroxidase (GOPOD reagent) for 20 min in 50 °C water bath, followed by absorbance measurement of the reacted mixture in a microplate reader. GOPOD was prepared according to the manufacturer's instruction to allow oxidation of D-glucose to D-gluconate with the release of equimolar amounts of hydrogen peroxide to be quantitatively measured in a colourimetric reaction employing peroxidase and the production of a quinoneimine dye. All reported values considered the correction for the reagent blank (deionised water) and were calculated against the glucose control (1 mg/mL) provided by the Megazyme assay kit. All the digestive supernatant collected from Section 2.4 were measured for D-glucose released (mg/g) in triplicates using the GOPOD reagent. The digested starch (%) was calculated using Eq. (1), where a conversion factor of 0.90 was used to convert from free glucose, as specified in the Megazyme kit, to anhydro-glucose, as occurs in starch. The total starch content of the French fry samples was determined using the Megazyme total starch assay kit (K-TSTA: AA/AMG) (Wicklow, Ireland) based on the AOAC Official Method 996.11 - DMSO format, taking into consideration the presence of resistant starch in the French fries.

$$\text{Digested starch } \% = \frac{\text{Glucose released} \times 0.90}{\text{Total starch content}} \times 100\% \quad (1)$$

Using the result from the *in vitro* starch digestibility assay, the proportions of rapidly digestible (RDS), slowly digestible (SDS) and resistant starch (RS) of French fries produced from potatoes with and without PEF pre-treatment were calculated (Pinhero et al., 2016). RDS and SDS were defined as the amounts of starch digested at 20 min during small intestinal phase, and between 20 and 120 min of digestion, respectively. RS represents undigested starch after 120 min which was calculated by deducting the total starch content of French fries with the sum of RDS and SDS.

#### 2.4.2. *Kinetic modelling on* in vitro *starch digestion*

Starch digestion during the small intestinal phase was modelled with a factional conversion model (Eq. (2)) (Khrisanapant et al., 2021) using SAS software (version 9.4 TS Level 1M2, SAS Institute, Inc., Cary, NC, USA) based on the non-linear regression function.

$$\text{starch}_t = \text{starch}_{intestine} + \left(\text{starch}_0 - \text{starch}_{intestine}\right) \times \exp^{(-k.t)} \quad (2)$$

where $\text{starch}_t$ is the digested starch (%) at any digestion time $t$ (min) during the small intestinal phase, $\text{starch}_{intestine}$ represents the estimated plateau of digested starch (%) at extended digestion times at small intestinal phase, and $k$ ($\text{min}^{-1}$) is the estimated reaction rate constant to describe the starch digestion kinetics in French fries at the small intestinal phase. Since digestibility is a continuous process comprised of enzymatic actions at oral, gastric and intestinal stages, it is important to note that $\text{starch}_0$ represents the digested starch (%) at the start of the small intestinal phase.

Kinetic modelling of the starch digestion data by a fractional conversion model allowed the estimation of three kinetic parameters ($\text{starch}_0$, $\text{starch}_{intestine}$ and $k$) to describe and subsequently compare the starch digestion kinetic behaviour in French fries produced from either untreated or PEF-treated potatoes. All modelled curves were assessed for model fitting between the experimental data and the predicted values by visually inspecting the residual and parity plots and calculating the corrected $R^2$ (Leong & Oey, 2012).

### 2.5. *Statistical data analysis*

The collated data was subjected to a one-way analysis of variance (ANOVA) using SPSS statistics version 26 (IBM Corporation, Endicott, NY, USA) to determine whether differences between No PEF treatment and PEF treatment existed. Significant differences ($p<0.05$) between means of different treatment were evaluated using post-hoc Tukey Honestly Significant Difference (HSD) test.

## 3. Results and discussion

The present study characterised the texture of French fries produced from either PEF treated or untreated whole peeled potato tubers, for two cultivars in an industrial processing plant. In addition the breakdown of starch was simulated during the gastrointestinal process to evaluate whether PEF pre-treatment had an influence on the digestibility of the starch in the resulting French fries.

### 3.1. *Crust hardness of French fries produced using potatoes with and without PEF pre-treatment*

In the frozen French fries processing industry, potatoes are partially fried (continuous mode) at high temperature for short time to reduce their moisture content and to create an outer thin crust layer prior to freezing. Before consumption, a second stage of frying process (batch mode) is performed to promote colour formation via Maillard reaction and development of a crispy outer crust. Table 1 summarises the crust hardness of French fries produced from either untreated or

**Table 1**
The effect of PEF pre-treatment on potatoes for two different varieties on the crust hardness and the appearance of the internal core region of the resulting French fries after finish frying (3 min at 180 °C).

| | Electric field strength (kV/cm) | Total specific energy input (kJ/kg) | Potato variety 1 – "Moderate DM" Dry matter range of tubers (%): 19.1–20.2 | | Potato variety 2 – "High DM" Dry matter range of tubers (%): 21.7–21.9 | |
|---|---|---|---|---|---|---|
| | | | Hardness of French fries crust after finish frying (N) | Appearance of internal core region of fries after finish frying[#] | Hardness of French fries crust after finish frying (N) | Appearance of internal core region of fries after finish frying[#] |
| No PEF[†] (Untreated) | – | – | 6.90 ± 2.25$^{c}$ |  | 8.51 ± 1.90$^{c}$ |  |
| PEF A | 1.1 | 2 | 12.00 ± 2.96$^{a}$ |  | 10.10 ± 3.00$^{bc}$ |  |
| PEF B | 1.9 | 7 | 10.89 ± 2.33$^{ab}$ |  | 12.94 ± 3.61$^{b}$ |  |
| PEF C | 1.1 | 50 | 9.43 ± 2.77$^{b}$ |  | 11.96 ± 3.93$^{b}$ |  |
| PEF D | 1.9 | 50 | 12.35 ± 4.72$^{a}$ |  | 16.32 ± 7.17$^{a}$ |  |

Data presented as mean ± standard deviation of ten independent fries. Superscript of different lower-case letters in the same column (within the same potato cultivar) indicate significant difference ($p<0.05$) between the means of the fries produced from potatoes pre-treated with different PEF process parameters, according to Tukey's HSD multiple comparison test.

[†] No PEF result was obtained from four independent batches of potatoes, which were sampled at the same time when each PEF process parameter was conducted at the industrial environment.

[#] Refer **Supplementary Material Table S1** for the colorimetric result ($L^*$, $a^*$, $b^*$ and browning index) of the outer surface of the French fries.

PEF-treated potato tubers after finish frying at 180 °C for 3 min (mimicking the typical preparation practice at restaurant, retail and household). Without the application of PEF pre-treatment on potato tubers (*i.e.* No PEF samples), fries produced from potato variety with "high DM" content (21.7–21.9%) appeared to require a higher cutting force (23.3% greater) to cut through the outer crust compared to those produced from potato variety with "moderate DM" (19.1–20.2%), after finish frying. This result is in agreement with a previous study in which potato cultivars with a DM content >21% (or high specific gravity) were reported to result in fried potato products with a harder, firmer, crunchier and crispy texture (Aguilar et al., 1997; Kita, 2002). The content of non-starch polysaccharides (*e.g.* pectin and cellulose) and lignin in potato tissues (Gołubowska, 2005; Lisińska & Gołubowska, 2005; Tajner-Czopek, 2003) is another vital physicochemical properties shaping the textural properties of the resulting French fries.

With respect to PEF-treated tubers, the resulting fries were significantly harder (up to 79% and 92% for "moderate DM" and "high DM" potatoes respectively) than fries from untreated tubers after finish frying (Table 1). The impact of PEF pre-treatment on potatoes on the textural properties of French fries is likely to due to the cell electroporation effect of PEF that can effectively modify the microstructure of the potato tissues prior to frying (Faridnia et al., 2015), resulting in a highly porous structure (Mhemdi et al., 2013) to facilitate the formation of a crust layer during frying. In addition, lesser amount of starch wash-out found in PEF-treated potato tubers (Fauster et al., 2018; Hill et al., 2022) is reported to increase hardness and crunch of potato snack products (Riaz, 2016; Zhang, Lyu et al., 2021). Since vapour movement to the surface and water evaporation from the surface are reported to occur at a faster rate for PEF-treated potato during frying (Liu et al., 2020), it is therefore reasonable to assume that crust formation could have been accelerated for PEF-treated potatoes at the par-frying stage. The boundary of evaporating water might start to move inwards as the potato surface dries out (Farkas et al., 1996), and thus contribute to the increase crust hardening at the second stage of frying. As more water is evaporated (*i.e.* at the surface and underneath the crust) from the fries, the external cells of the fried potato tissue continuously loses moisture and the crust progressively becomes dryer and harder. Clearly, the texture result obtained in this study suggests that the rate of the abovementioned phenomena is faster for French fries produced using PEF-treated potatoes compared to fries from untreated potatoes. Another key finding from the current study is that the crust hardness of fries from potatoes with "high DM" content appeared to increase in a PEF process intensity-dependant manner, a result which was not observed in fries from PEF-treated potatoes with "moderate DM" content. Specifically, fries from PEF-treated tubers with "high DM" content exhibited increasing hardness in outer crust according to the increase intensity of PEF process parameters, when elec-

tric field strength increased from 1.1 to 1.9 kV/cm and energy input from 7 up to 50 kJ/kg (*i.e.* PEF B, PEF C and PEF D). Similar to French fries, PEF pre-treatment on potato tuber can lead to production of potato crisps (fried potato slices) with a harder texture, as evidenced by both the texture measurement and sensory evaluation by human participants (Cahayadi et al., 2020).

Transverse sections of the internal core region of fries produced from either untreated or PEF-treated potato tubers are presented in Table 1. The work of Yin and Panigrahi (2004) describes a good quality French fry as being characterised by an interior (core region) which has a floury/mealy texture similar to baked/cooked potato. Fries with a watery or mushy internal texture and which show an apparent separation between the core and the crust and hence the presence of internal hollowness or separation are undesirable. With respect to fries produced from potatoes with "moderate DM" content, the internal hollowness was not observed for fries from untreated tubers and those that had received low electric field strength PEF treatments (PEF A and PEF C) at 1.1 kV/cm at either low (2 kJ/kg) or high energy (50 kJ/kg). However, an internal hollowness was rather obvious for fries produced from "moderate DM" potatoes pre-treated at an electric field strength of 1.9 kV/cm (PEF B and PEF D) and this undesirable internal texture feature intensified with the application of high-energy input PEF treatment at 50 kJ/kg. It must be emphasised that the presence of internal hollowness in these fries was not detected at their par-fried state (before finish frying). With respect to fries produced from tubers with "high DM" content, the presence of internal hollowness after finish frying appeared to be an inherent characteristic for the resulting fries of this cultivar even in tubers that had not received a PEF pre-treatment.

Overall, the application of PEF pre-treatment at high electric field strength of 1.9 kV/cm and energy input of 50 kJ/kg (*i.e.* PEF D) negatively affected the internal hollowness of the resulting fries from both potato varieties, accompanied with a severe separation of core from the crust that was not observed in other PEF-treated fries. It has been proposed that the presence of internal hollowness in fries could be due to excessive pressure build-up of evaporating water in the core region during frying, where the potato cells are pushed away more vigorously as water vapour forces its way outside through the hard crust layer (Van Loon et al., 2007). Another possible explanation could be that quick moisture loss during frying led to excessive shrinkage of potato cells due to dehydration, thus separating the neighbouring potato cells, filled with gelatinised starch, away from each other (Millin et al., 2016). Moreover, a recent study by Moens et al. (2021) reported a significant reduction in the degree of methyl-esterification of pectin in potatoes after PEF pre-treatment, which consequently decreased the cell wall strength, disrupted the middle lamella between cells and affected cell-to-cell adhesion in the potato tissue. As reported in previous studies, the application of PEF pre-treatment could interfere with the water redistributions within the plant tissues (Dellarosa et al., 2016; Tylewicz et al., 2016) and increase the water mass transfer process (Traffano-Schiffo et al., 2016), which could have also contributed to the development of hollowness in fries after finish frying.

The current study demonstrated that an application of PEF pre-treatment on potatoes of two different cultivars with moderate to high DM content (19–22%) equally resulted in French fries with harder crusts at finish frying. In particular, the fries produced using potatoes with "high DM" content followed a clear increasing trend between the hardness of outer crust and the intensity of PEF process parameters applied to the tubers. The application of high-energy and high intensity electric field PEF process parameters should be avoided to minimise development of undesirable hollowness in the fries. For process control and to avoid over-processing, impedance or cutting force measurement have been suggested (Fauster et al., 2018). The use of advanced microscopy and tomography imaging techniques is also recommended in future studies to better explain the physical, mechanical, morphology and structural changes in both the outer crust and internal core regions of French fries from PEF-treated potatoes during par- and finish frying.

### 3.2. Starch digestibility of French fries produced using potatoes without PEF pre-treatment

French fries has been reported to elicit a lower glycaemic response (*i.e.* glycaemic index (GI) ranged between 38 and 76) in the postprandial phase after consumption when compared to other potato-based food products prepared using other processing methods such as boiling, baking and roasting (*i.e.* GI ranged between 48 and 93) (Lynch et al., 2007; Nayak et al., 2014). This is because of the presence of oil in the French fries limits the accessibility of the digestive enzymes to the starch. Since fries from "high DM" potatoes had a higher oil content (3.5–4.3%) compared to fries from "moderate DM" potatoes (3–4.2%) (Table 2), it is expected that the fries made from the two potato cultivars would exhibit different starch digestibility behaviour.

During French fries production, potato starch is gelatinised during the blanching and par-frying steps and then retrograded (*i.e.* starch tends to reassociate to recover the crystalline order) upon freezing which may result in the formation of starch fractions with higher resistance to digestion by amylase enzyme and hence a reduced starch digestion rate (Lynch et al., 2007) and a lower GI (Englyst et al., 1996). In the present study, the ratio of three starch fractions in the potato fries varied between cultivars, where fries from potatoes with "moderate DM" content exhibited a higher %RDS and a much lower %SDS of total starch during *in vitro* digestion (Table 2). However, the high %RDS of total starch found in "moderate DM" fries was not matched by the large decrease in indigestible %RS. Instead, the high %RS observed in "moderate DM" fries correspond with a low %SDS. Hence, fries produced using "high DM" containing tubers exhibited a desirable digestible starch profile from a nutritional perspective because of their low %RDS and high %SDS (Bach et al., 2013). This result suggests that a larger proportion of retrograded starch in French fries from "high DM" potatoes are digested at a slower rate and only a small proportion of starch is in the indigestible RS form. Considerable variation in the ratio of RDS, SDS and RS fractions between potato cultivars has been reported in previous studies (Bach et al., 2013; Li, George et al., 2019; Monro et al., 2009; Pinhero et al., 2016), largely due to the chemical differences in their amylose-amylopectin ratios and starch crystallinity.

During the small intestinal digestion, the % of digested starch was modelled using a fractional conversion model (Eq. (2)), which described the exponential increase in % digested starch with increasing digestion time (up to 4 h small intestinal digestion), after which the % digested starch reaches a plateau value (Fig. 2). This appears to be the first study to report on the % of the various forms of digested starch during an extended small intestinal phase ($starch_{intestine}$) and to present the reaction rate constant ($k$) which describes the kinetics of starch digestion (or glucose release) in French fries during the small intestinal. As shown in Table 2, the starch in "moderate DM" fries exhibited a lower digestion rate (58% slower in $k$), during the simulated small intestinal phase, in comparison to the "high DM" fries although the total starch content of French fries produced from both potato varieties was very similar (averaged at ~17%, Table 2). The estimated starch digestion rate aligned with a lower %SDS and a higher %RS for "moderate DM" fries. After a prolonged small intestinal digestion, a larger amount of starch was estimated to be hydrolysed ($starch_{intestine}$) for "high DM" fries (82%) compared to "moderate DM" fries (66%), which corresponded with the lower undigestible %RS observed in "high DM" fries. Therefore, the two estimated kinetic parameters ($k$ and $starch_{intestine}$) complemented the proportions of RDS, SDS and RS to indicate the nutritional implications of the digestibility of starch in the French fries.

### 3.3. Starch digestibility of French fries produced using potatoes with PEF pre-treatment

An earlier study from Ignat et al. (2015) reported that PEF application (0.75–2.5 kV/cm, 18.9 kJ/kg) may trigger the leakage of starch from potatoes (*i.e.* indicated by an increase in turbidity of the blanching

**Table 2**
Summary of the total starch and oil contents, proportions of starch fractions and the estimated kinetic parameters of *in vitro* starch digestion at the simulated small intestinal phase for French fries produced from untreated and PEF-treated potatoes.

| | Total starch content (%)* | Oil content (%)* | Proportion of starch fraction (%)* | | | Estimated kinetic parameters of *in vitro* starch digestion** | | |
|---|---|---|---|---|---|---|---|---|
| | | | RDS | SDS | RS | $k$ ($\times 10^{-2}$ min$^{-1}$) | starch$_{intestine}$ (%) | Corrected $R^2$ |
| Potato variety 1 – "Moderate DM" | | | | | | | | |
| No PEF† | 16.99 ± 2.55 | 4.30 ± 0.44$^{ab}$ | 28.21 ± 7.27 | 27.03 ± 2.31$^{b}$ | 44.76 ± 4.01 | 1.07 ± 0.18 | 65.67 ± 2.62 | 0.8749 |
| PEF A | 18.75 ± 1.53 | 3.99 ± 0.04$^{ab}$ | 30.46 ± 1.20 | 23.51 ± 1.18$^{b}$ | 46.04 ± 1.18 | 1.01 ± 0.26 | 61.18 ± 3.81 | 0.9198 |
| PEF B | 18.11 ± 1.77 | 4.77 ± 0.19$^{a}$ | 25.30 ± 2.16 | 34.26 ± 0.22$^{a}$ | 41.53 ± 1.71 | 0.86 ± 0.11 | 79.38 ± 3.69 | 0.9797 |
| PEF C | 18.06 ± 2.18 | 3.46 ± 0.18$^{b}$ | 27.99 ± 2.65 | 29.42 ± 3.77$^{ab}$ | 42.59 ± 2.53 | 1.66 ± 0.52 | 61.24 ± 2.89 | 0.8502 |
| PEF D | 21.30 ± 1.51 | 3.95 ± 0.09$^{ab}$ | 31.12 ± 1.06 | 23.60 ± 2.38$^{b}$ | 45.28 ± 3.23 | 0.67 ± 0.17 | 82.16 ± 7.40 | 0.9483 |
| Potato variety 2 – "High DM" | | | | | | | | |
| No PEF† | 17.00 ± 2.95 | 3.30 ± 0.76 | 19.46 ± 2.66$^{b}$ | 55.88 ± 4.96$^{a}$ | 24.74 ± 1.98$^{d}$ | 1.69 ± 0.15 | 82.35 ± 2.05 | 0.9569 |
| PEF A | 17.60 ± 1.57 | 4.19 ± 0.12 | 27.42 ± 1.40$^{a}$ | 41.62 ± 1.54$^{b}$ | 29.97 ± 1.54$^{bc}$ | 1.62 ± 0.32 | 75.20 ± 3.18 | 0.9044 |
| PEF B | 17.70 ± 2.69 | 3.00 ± 0.08 | 22.91 ± 3.12$^{ab}$ | 38.43 ± 1.56$^{b}$ | 38.66 ± 3.73$^{a}$ | 1.61 ± 0.18 | 68.30 ± 1.89 | 0.9637 |
| PEF C | 17.27 ± 1.92 | 3.16 ± 0.15 | 22.07 ± 0.96$^{ab}$ | 53.77 ± 3.02$^{a}$ | 24.16 ± 3.98$^{d}$ | 1.84 ± 0.26 | 86.68 ± 3.01 | 0.9484 |
| PEF D | 17.75 ± 1.16 | 2.95 ± 0.32 | 26.41 ± 0.36$^{ab}$ | 37.75 ± 2.81$^{b}$ | 35.84 ± 2.88$^{ab}$ | 1.48 ± 0.25 | 68.36 ± 2.91 | 0.9328 |

DM: dry matter, RDS: rapidly digestible starch, SDS: slowly digestible starch, RS: resistant starch.

* Data presented as mean ± standard deviation of three independent measurements. Superscript of different lower-case letters in the same column (within the same potato cultivar) indicate significant difference ($p<0.05$) between the means of the fries produced from potatoes pre-treated with different PEF process parameters, according to Tukey's HSD multiple comparison test.

** Data presented as estimated kinetic parameter ± asymptotic standard error of estimated parameter at 95% confidence intervals using SAS software based on non-linear regression analysis using a fractional conversion model (Eq. (2)).

$k$ represents the estimated reaction rate constant to describe the starch digestion kinetics in French fries at the small intestinal phase.

starch$_{intestine}$ represents the digested starch (%) at the end of small intestinal phase.

† No PEF result was obtained from four independent batches of potatoes, which were sampled at the same time when each PEF process parameter was conducted at the industrial environment.

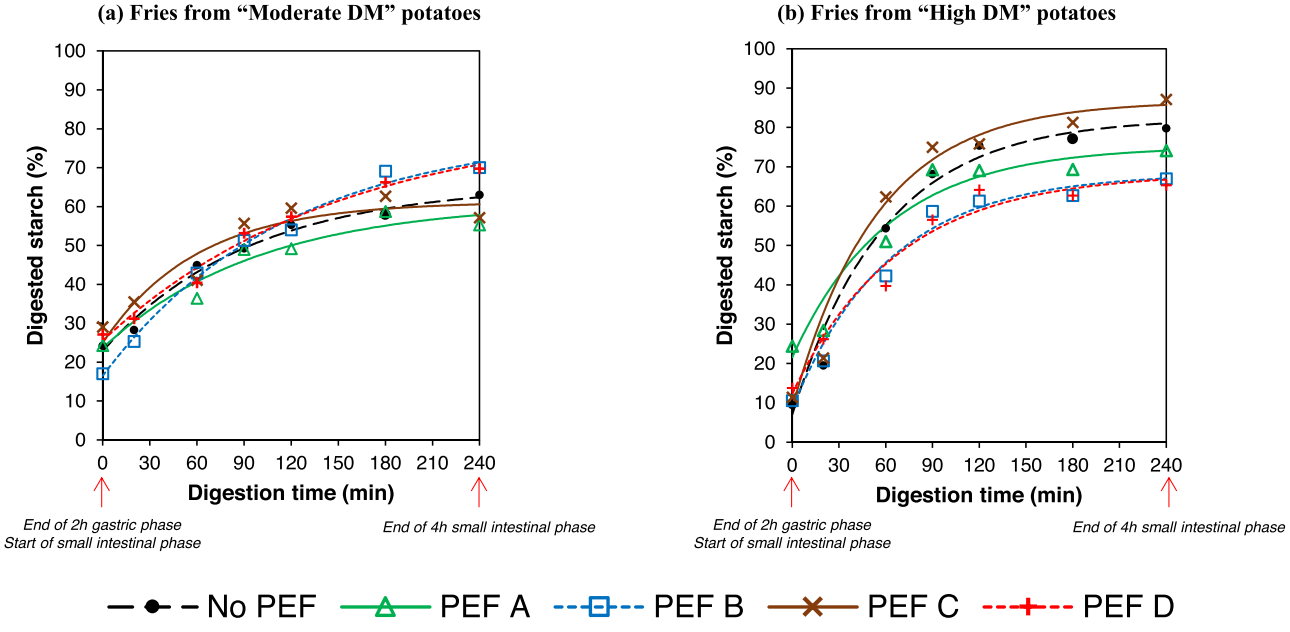


**Fig. 2.** *In vitro* starch digestion kinetics at small intestine phase for French fries produced from untreated and PEF-treated potatoes with either "moderate DM" (<20%) or "high DM" (>21%) content. Data points are experimental values of digested starch of French fries from untreated (●), PEF A (Δ), PEF B (□), PEF C (×) and PEF D (+) -treated potatoes. Lines are the predicted values from the factional conversion model (Eq. (2)).

water). However, unlike in the previous study, there were no significant differences in the total starch content between fries produced from either PEF treated or untreated potatoes produced under industrial processing for either cultivar (Table 2). The current results clearly show that the application of PEF at an electric field strength up to 1.9 kV/cm and energy input up to 50 kJ/kg did not facilitate any significant starch loss from potatoes. This can be explained by the fact that the size of potato starch granules generally vary from 1 up to 85 μm and are mostly found in the vascular tissue (Singh & Kaur, 2004) while the diameter of pores on potato cell membrane formed by PEF average between 10 and 21 nm (Zhang et al., 2022) and never exceed 5 μm (Bazhal et al., 2003). Following PEF, the fries were blanched causing the starch to swell and become gelatinised and hence, become too large to pass through the electroporated potato cells. In line with this, it has been reported that starch losses into processing water streams are heavily reduced after PEF processing (Fauster et al., 2018; Hill et al., 2022).

The starch digestibility of French fries from untreated or PEF-treated tubers with "moderate DM" content was compared, and three key findings were observed (Table 2). Firstly, fries produced from either PEF-treated or untreated tubers at low electric field strength (PEF A) had a similar %RDS, %SDS, %RS, starch digestion rate ($k$) and final % starch hydrolysis (*starch*$_{intestine}$). Secondly, fries produced after the application of low PEF electric field strength and high energy (PEF C) exhibited a 55% faster starch digestion rate (from 1.07 to 1.66 $\times 10^{-2}$ min$^{-1}$)

which did not correspond to a large increment in the amount of starch estimated to be completely digested by the end of small intestinal digestion ($starch_{intestine}$), and did not significantly affect the proportions of the three starch fractions. The increased rate of starch hydrolysis in PEF C fries is likely to have occurred owing to the considerably lower amount of oil found in the fries (Table 2), which enabled the digestive enzymes to better penetrate into the French fry matrix and hydrolysing the starch into glucose. Thirdly, the fries produced from tubers pre-treated with a higher electric field strength (1.9 kV/cm, PEF B and D) had between a 20 and 37% decline in their starch digestion rate but a higher total amount of starch was digested ($starch_{intestine}$ increased from 66% to 79 and 82%) in comparison to fries produced from untreated potatoes. Despite this the %RDS and %RS for fries from PEF B and PEF D were not affected. However, a slower digestion rate for PEF B fries corresponded to a significant increase in %SDS, which correlated with their higher oil content (Table 2). This is because frying process can promote formation of amylose-lipid complexes (Nayak et al., 2014) and the high oil content in French fries (Singh et al., 2020) may slow down the digestibility of starch. While PEF has been reported to induce changes in the physicochemical properties of isolated potato starch (*i.e.* shifting the starch gelatinisation temperature range and changes in the starch solubility, swelling power and crystallinity) which has been reported to impact on starch digestibility (Cao & Gao, 2019; Han et al., 2009; Li, Wu et al., 2019), this theory is not substantiated by the present study with respect to fries from potatoes with a "moderate DM" content due to the significant high oil content found in the PEF B fries compared to the untreated fries.

With respect to the starch digestibility behaviour of fries produced using potatoes with "high DM" content, any PEF pre-treatment did not influence the rate ($k$) of glucose release during *in vitro* gastrointestinal digestion (Table 2). The fries from "high DM" tubers PEF-treated at low field strength and high energy (PEF C) had a similar starch digestion profiles and kinetics of glucose release during small intestinal phase as the untreated fries. However, fries from potatoes pre-treated with PEF at low electric field strength and energy (PEF A) had a shift in the starch fractions towards higher RDS, lower SDS and increased RS, compared to untreated fries. An increase in %RS for PEF A fries corresponded with more starch estimated to be undigested after prolonged intestinal phase (*i.e.* indicated by a decline in $starch_{intestine}$). Moreover, a decline in %SDS, an increase in %RS and a reduction in $starch_{intestine}$ occurred in fries produced from potatoes pre-treated with a high electric field strength (PEF B and PEF D), indicating a slower release of glucose from "high DM" fries during the final small intestinal digestion phase. The reduction of starch digestibility could imply a slower and more sustained release of glucose which has been reported to improve the postprandial response in individuals with type 2 diabetes and may also prolong satiation (Ek et al., 2012). In this context, a recent study by Cahayadi et al. (2020) has revealed that potato crisps produced using PEF-treated potatoes appeared to be more satiating than crisp produced from untreated potatoes.

It is worthy to highlight that the oil content in "high DM" fries was not significantly affected by the application of PEF treatment when compared to "moderate DM" fries (Table 2), therefore the oil content might be having relatively little impact on the reduced starch digestibility of "high DM" fries. Previous studies have reported a similar pattern of starch digestibility as reflected by a decrease in %SDS and an increase in %RS in rice starch (Wu et al., 2019; Zeng et al., 2016) and starch isolated from wheat, potato and pea (Li, Wu et al., 2019) after PEF treatment. However, these previous studies used PEF at a much higher intensity of electric field strength (up to 50 kV/cm) and changes in the crystallinity of gelatinised starch due to retrogradation by cooling or freezing were not considered. In view of the drastic changes that occur in potato starch, from gelatinisation to retrogradation, throughout the multi-processing stages of French fry production, there is very little information to clarify whether changes in the proportions of RDS, SDS and RS, and the kinetics of starch digestion as observed in "high DM" fries are mainly driven by the application of PEF treatment. This aspect can present as a subject of further research to systematically investigate the complex effect of PEF and starch retrogradation, in conjunction with the potential amylose-lipid interaction due to the presence of oil, on the structural and crystallinity of starch leading to the production of French fries or other cooked potato products with different starch digestion profiles.

The overall results from the *in vitro* starch digestibility assay showed that the potato cultivar effect dominates the very large differences in the starch digestion profiles and kinetics of starch digestion of French fries compared to the application of PEF pre-treatment on potatoes prior to French fries production. While PEF pre-treatment on potato tubers appeared to produce French fries with variable %RDS, %SDS and %RS and starch digestion kinetics, this can been explained by the presence of a high oil content in the fries which limits the accessibility of digestive enzymes to hydrolyse starch. The complex production steps and reactions occur during in French fry production which involving starch retrogradation during cooling and storage that can impact on starch crystallinity and digestion behaviour of starch are contributing factors as well. It should be emphasised that the impact of PEF pre-treatment on a single potato cultivar is likely to be subtle and may not lead to a significant nutritional consequence by impacting on their GI.

## Conclusion

Regardless of the inherent DM content of potatoes, this study showed that PEF pre-treatment enabled the formation of an outer crust on French fries after the final frying step which had an increased hardness compared to fries made from tubers without PEF pre-treatment. PEF pre-treatment step likely affected the extent of water loss during frying. In line with this, the use of PEF in French fries industry may provide additional advantages in reducing the frying condition (both temperature and time) and oil consumption, thereby increasing the production yield without compromising the texture of the outer crust. Future investigation should consider optimising the frying condition (par-frying and finished frying) of fries produced using PEF-treated tubers to better meet consumer's acceptability on the crust hardness. The current study has also revealed that the hydrolysis of starch in French fries during *in vitro* digestion is mainly driven by cultivar effect. The effect of PEF pre-treatment on the starch digestibility of French fries was more evident in a potato cultivar which had a "high DM" content, where PEF fries (after application of high electric field strength at 1.9 kV/cm) had a lower %SDS and a higher %RS. From a nutritional point of view, a shift in the starch digestion profiles in PEF fries towards those with a reduced release of glucose in the gut will result in a lower postprandial insulin peak, which may prolong satiation and potentially reduce health-related risk factors associated with the frequent consumption of French fries. Findings from the *in vitro* starch digestibility behaviour for PEF pretreated French fries would serve as a basis for future studies to examine their starch digestion and glycaemic responses *in vivo*.

## Ethical statement - studies in humans and animals

This study did not involve humans and animals.

## Declaration of Competing Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. The potato tubers were provided by a local French fries manufacturing company; hence the source and the name of potato cultivar are unable to be disclosed publicly.

## CRediT authorship contribution statement

**Sze Ying Leong:** Conceptualization, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing –

original draft, Writing – review & editing. **Rebecca Roberts:** Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft. **Zhihao Hu:** Data curation, Formal analysis, Investigation, Validation. **Phil Bremer:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing. **Patrick Silcock:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing. **Stefan Toepfl:** Conceptualization, Methodology, Resources, Software, Writing – review & editing. **Indrawati Oey:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2022.100194.

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