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Using a novel spiral-filter press technology to biorefine horticultural by-products: The case of tomato. Part I: Process optimization and evaluation of the process impact on the antioxidative capacity

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ABSTRACT

With tomato as a model crop, the use of a novel, low-oxygen spiral-filter press technology for juice production was demonstrated on pilot-scale. Our results show that a robust process could be developed with a juice yield of 82.5% which could be increased to 97.0% with an additional mild thermal pretreatment (40 °C for 3 min). A comprehensive insight was gained in the underlying mechanisms through which process parameters can affect juice yield and juice quality parameters such as turbidity and precipitate weight ratio. Additionally, the antioxidative capacity (AOC) was investigated, showing a preservation of antioxidants during pressing (102 ± 12%) which may be attributed to the low-oxygen processing. Finally, also an insight was gained in the antioxidative distribution of the resulting fractions, demonstrating the potential of the press residue and confirming the relevance of designing a biorefinery system where all fractions are valorized.

Industrial relevance: This pilot-scale study illustrates the potential of a novel spiral-filter press technology in refining biomass. Besides a high juice yield and retention of the antioxidative potential, it proves flexible towards characteristics of the input biomass and can customize end-products in function of the aimed application. This study contributes to the essential technical knowledge necessary for processing other matrices with this novel technology.

1. Introduction

Globally, one third of the edible food is lost (1.3 10^6 ton·year^{-1}) (Gustavsson, Cederberg, & Sonesson, 2011). The fruit and vegetable processing sector, with losses of 40–60% in their production process (e.g. overproduction, edible and inedible processing by-products and waste fractions), is a sector where one of the largest quantities of healthy and potentially high-value biomass remains unused (Bos-Brouwers, Langelaan, Sanders, van Dijk, & van Vuuren, 2012; Gustavsson et al., 2011). Conversely, biomass plays a key role in the emerging bioeconomy where it is used as input for the production of a wide range of products. It is conceived that in this more sustainable economy, products are produced via biorefineries, following a cascade principle in order to maximally valorize the available biomass (Flemish government, 2013; McCormick & Kautto, 2013). Combining both factors, i.e. using food losses in the bioeconomy through a biorefinery process, would thus convert a problem into an opportunity for the emerging bioeconomy.

However, there are a number of factors currently impeding the valorization of fruit and vegetable by-products. A literature screening (e.g. HLPE, 2014; Schieber, Stintzing, & Carle, 2001) and interviews with stakeholders show that their valorization is currently mainly impeded by their high moisture content (often >90%) and corresponding fast decay, their relatively small and geographically dispersed volumes and the seasonality of their production. The combination of these factors makes their collection, conservation and processing a major challenge (OVAM, 2014).

In this study, the capability of a novel low-oxygen spiral-filter press to biorefine fruit and vegetable biomass is evaluated. Due to its flexibility and modular design, this spiral-filter press can tackle the above mentioned impeding factors, making it a promising technology. First, using a pressing technology in general for valorizing fruit and vegetable by-products optimally addresses the first challenge mentioned, namely

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Abbreviations: MT, mashed tomatoes; TT, thermally treated tomato; JFO, juice filtered once; PR, press residue; JFT, juice filtered twice; TS, tomato solids; S, spiral frequency; V, vacuum pump frequency; M, pore size of the filter element; C, number of channels of the spiral; MC_{PR}, moisture content of the press residue; MC_{MT}, moisture content of the mashed tomatoes; MC_{JFO}, moisture content of the juice fraction; JY, juice yield; TH, throughput; TU, turbidity; PWR, precipitate weight ratio; AOC, antioxidant capacity.

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the high moisture content. Instead of stabilizing the biomass by using expensive or quality-reducing drying techniques such as hot air drying (Jangam, 2011), juice pressing extracts a large part of the liquid content that subsequently can be valorized as fruit or vegetable juice or related products. Second, the spiral-filter press can deal with the seasonality and variable volumes of horticultural by-products. Preliminary experiments have shown that the press is able to process a range of volumes (300–28,000 $k\cdot.h^{-1}$) as well as handle a multitude of different textures (e.g. apples, berries, corn, carrots, nuts, …), due to its modular nature and its flexible process parameters (Siewert, 2013). Hence, multiple biomass streams can be processed in function of the harvesting season, which is not the case with some conventionally used presses such as the widely used belt-press which is only suitable for hard biomass matrices such as apple and pear or the Bucher horizontal piston press, working in batch mode (Barrett, Somogyi, & Ramaswamy, 2005; Beveridge & Rao, 1997). Moreover, due to its flexibility, it can be used as a key technology in biorefineries, because it allows a further unraveling and dissection of the resulting solid and liquid streams into multiple fractions, thereby creating a higher added-value compared to the direct use of the whole by-product as such (Baiano, 2014; Bos-Brouwers et al., 2012). An important additional advantage of the spiral-filter press is the quality of the resulting premium, cloudy juices, in contrast to the Bucher horizontal piston press and the decanter centrifuge, generating rather clarified juices with low soluble solids content (Barrett et al., 2005; De Paepe et al., 2015a, 2015b). Finally, the spiral-filter press can conserve the phenolic composition of the input biomass throughout processing, which can be attributed to the juice extraction under low-oxygen atmosphere, preventing oxidation from taking place (De Paepe et al., 2015a, 2015b). In general, conventional presses such as the belt-press and the Bucher horizontal piston press work open to the atmosphere, allowing oxidation and subsequent product degradation. For apple, a comparison of the performance of the spiral-filter press with the belt-press has been performed, showing (i) a higher juice yield, (ii) a higher juice turbidity and (iii) a higher retention of phenolic compounds during downstream processing steps and storage for the former (De Paepe et al., 2015b). Also the juice extraction process using pulper and finisher, specifically used for tomato juice processing to separate the peels and seeds from the juice, is characterized by a high rate of oxygen absorption caused by a high rotation speed open to the atmosphere (Noomhorm & Tansakul, 1992).

The spiral-filter press thus has the potential to serve in small and medium size enterprises (SME) context to produce premium juices derived from multiple biomass feedstocks and by-products. Even though being flexible towards the nature of the starting material, biomass processing with the spiral-filter press does require an optimization per matrix and comprehensive insights in the working principle of the press are needed in order to exploit its broad working range. To date, only limited scientific studies have evaluated the performance of the spiral-filter press, focusing on the processing of apple, pear and strawberry (De Paepe et al., 2015a, 2015b; Possner, Ludwig, Hirn, Will, & Dietrich, 2015). As a result, detailed process parameters and knowledge about the press' working principle, that are broadly applicable to other matrices, are particularly uncommon. This paper offers a comprehensive insight in these aspects by using underutilized tomatoes (e.g. surplus product, low quality tomatoes) as a model crop to investigate the use of the spiral-filter press to biorefine and valorize horticultural by-products. Annually, over 6000 tons of healthy tomatoes remain unsold at the auctions in Belgium, leaving high-value valorization options unused (personal communication, Belgian auctions). In addition, the conventional tomato processing industry (i.e. washing, sorting, crushing, preheating (hot/cold break), pulping/finishing using screens and evaporation) in Belgium is absent, impeding a potential valorization of these tomatoes (Hayes, Smith, & Morris, 1998; Heutink, 1986). Furthermore, in contrast to apples and pears, it is a soft matrix which implies that other technical processing challenges have to be addressed, which are in their turn applicable for similar berry-like matrices. The focus in this paper thus lies in understanding the underlying mechanisms of the spiral-filter press through which process parameters affect juice yield and juice quality when processing soft matrices, by comparing different pilot-scale experiments with different parameter sets. Furthermore, the antioxidant capacity of the resulting samples was related to the feedstock, in order to discern the impact of processing on the raw fruit/vegetable and achieve a relevant indication of the process impact.

The approach adopted here consisted of a pilot-scale optimization of the parameters necessary for a basic solid-liquid separation using the spiral-filter press (Fig. 1, dotted line). The resulting end-products were analyzed for their antioxidative capacity in order to evaluate the process impact of the low-oxygen spiral-filter press on the oxidation of the biomass. In a second step, the optimized system was developed towards further refining the tomato biomass, using the insights gained in the first step (Fig. 1, solid line). This was achieved by (ii) applying a thermal pretreatment (analogous to conventional tomato processing using cold/hot break) to produce a press residue, separable into whole seeds and peels and (iii) by performing a second solid-liquid separation of the juice obtained in the first phase, in order to isolate a firm tomato puree (tomato solids) from the tomato juice.

2. Materials and methods

The optimization of the biorefinery process was performed in several steps (Fig. 1). These steps will be subsequently covered hereafter.

2.1. Optimization of the first solid-liquid separation

The first step in the optimization process was to investigate if the juice yield obtained by the spiral-filter press could be maximized without using an additional heat pretreatment. Therefore, the process depicted in Fig. 1 is simplified and comprised only the milling step and the first solid-liquid separation (shown by the dotted line).

2.1.1. Description of the machinery and the optimization process

Intact tomato fruits, resulting from overproduction and consisting of a mixture of cultivars (predominantly Kanavaro flesh tomato), were provided by a Belgian auction (REO, Roeselare, Belgium) (Supplementary data 1). The majority (~95%) was at commercial maturity. A homogenized batch of 500 kg was collected in a water bath, filled with cold tap water until all tomatoes were submerged. Subsequently, they were transported by a conveyor into a mill, rotating at a constant angular speed (20 $kg\cdot h^{-1}$) (KWEM 1000, Kreuzmayr, Wallem, Germany). The mashed tomatoes were ejected into the buffer tank of the spiral-filter press, which is the central part in the biorefinery process (Supplementary data 2). This system consists of a buffer tank, a screw pump (feed pump), an extraction cell, a spiral that rotates in a cylindrical sieve, a vacuum pump and two exits for liquid and solid fractions, respectively (De Paepe et al., 2015a, 2015b).

The optimization process started with evaluating the system parameters for the first solid-liquid separation: feed pump frequency (F [Hz], 0–50 Hz), spiral frequency (S [Hz], 0–50 Hz), vacuum pump frequency (V [Hz], 0–50 Hz), pore size of the filter element (M [μm], 60, 100, 150 and 300 μm) and number of channels of the spiral (C [−], 3, 4 or 7). The shaft inclination angle was kept constant at an constant angle of 45°. Furthermore, due to practical considerations, a constant feed pump frequency F of 20 Hz was used in all experiments, leading to a system with four variable system parameters. The effect of varying these system parameters was evaluated on the juice yield (JY) and the moisture content of the press residue (MC_{PR}). However, in order to get a better insight in the process, various other dependent variables were also recorded such as the moisture content of the other fractions (moisture content of the mashed tomato, MC_{MT}; moisture content of the juice filtered once, MC_{JFO}), the total throughput (TH), the turbidity of the juice (TU) and the precipitate weight ratio (PWR). A total of sixteen combinations were tested according to a screening design configuration

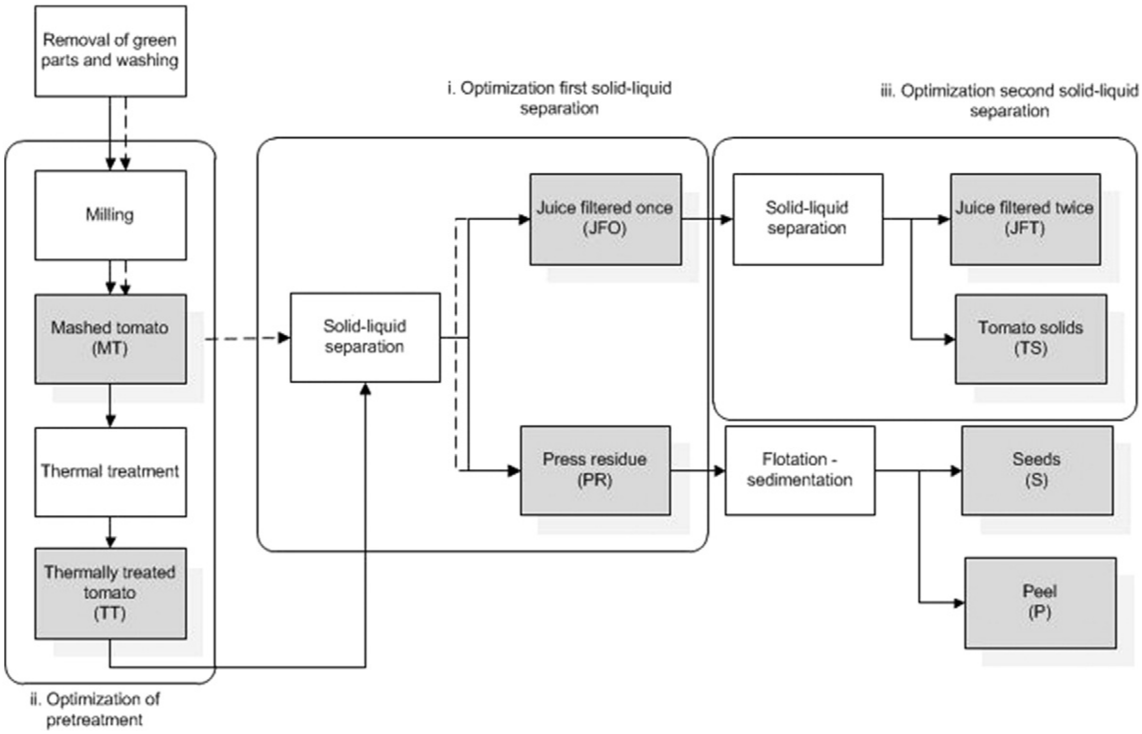

Fig. 1. Visualization of the optimized biorefinery process. The processes are represented by white boxes and the resulting products by grey boxes. The optimizations for the different subprocesses are indicated by grouped boxes. The dotted lines represent the start of the optimization using a simplified process.

(Table 1). It has to be noted that the mentioned frequencies represent a rescaled value of the real rotation frequency, for which the correlations are attached in Supplementary data 3 (De Paepe et al., 2015a).

2.1.2. Description of the sampling and recording of the dependent variables

After each well-defined process step, samples were taken to investigate the process impact on the quality of the end-products. These are represented by the grey boxes in Fig. 1 and consist of mashed tomatoes (MT), juice filtered once (JFO) and press residue (PR) in the first solid-liquid separation process. The analyses of JY, MC, TU and PWR were performed on all freshly taken samples, whereas only the samples resulting from the conditions generating the highest juice yield were frozen at −20 °C, freeze-dried (Epsilon 2–10 D LSC, Martin Christ, Osterode am Harz, Germany) and subsequently analyzed for their antioxidant capacity (AOC).

Table 1
Screening design used in the optimization of the first solid-liquid separation with the real (C, M, S, V) and the coded (c, m, s, v) independent variables.

Experiment	Number of channels [−] C (c)	Pore size filter [μm] M (m)	Spiral frequency [Hz] S (s)	Vacuum pump frequency [Hz] V (v)	Measured juice yield [%] JY
1	7 (+1)	100 (−1)	10 (−1)	0 (−1)	24.1
2	7 (+1)	100 (−1)	50 (+1)	0 (−1)	42.8
3	7 (+1)	100 (−1)	10 (−1)	50 (+1)	20.3
4	7 (+1)	100 (−1)	50 (+1)	50 (+1)	49.8
5	7 (+1)	300 (+1)	10 (−1)	0 (−1)	30.5
6	7 (+1)	300 (+1)	50 (+1)	0 (−1)	43.2
7	7 (+1)	300 (+1)	10 (−1)	50 (+1)	30.3
8	7 (+1)	300 (+1)	50 (+1)	50 (+1)	76.8
9	4 (−1)	100 (−1)	10 (−1)	0 (−1)	23.9
10	4 (−1)	100 (−1)	50 (+1)	0 (−1)	31.3
11	4 (−1)	100 (−1)	10 (−1)	50 (+1)	24.7
12	4 (−1)	100 (−1)	50 (+1)	50 (+1)	54.1
13	4 (−1)	300 (+1)	10 (−1)	0 (−1)	25.2
14	4 (−1)	300 (+1)	50 (+1)	0 (−1)	27.8
15	4 (−1)	300 (+1)	10 (−1)	50 (+1)	59.1
16	4 (−1)	300 (+1)	50 (+1)	50 (+1)	82.5

The JY of the first solid-liquid separation process was determined by recording mass balances of the JFO and PR during the steady-state phase of the process. The JY was determined as $\mathrm{JY} = \frac{M_{\mathrm{JFO}}}{M_{\mathrm{JFO}}+M_{\mathrm{PR}}} \times 100\%$ with M_{JFO} the net mass of the juice and M_{PR} the net mass of the press residue. The total TH was calculated analogously: $\mathrm{TH} = \frac{M_{\mathrm{JFO}}+M_{\mathrm{PR}}}{t}$ with t the time during which both fractions were collected.

The MC measurements were performed in duplicate using a halogen moisture analyzer (HB43-S, Mettler Toledo, Schwerzenbach, Switzerland). The TU was measured nephalopmetrically using a light scattering photometer (Micro1000 Laboratory Turbidity meter, HF scientific, Florida, USA). These TU measurements were performed three times on a homogeneous sample. PWR was measured gravimetrically (PB3002-S, Mettler-Toledo, Greifensee, Switzerland) by calculating the ratio of the mass of 30 g juice (M_0) and the net mass of sediment resulting after centrifugation (4200 g, 15 min) of the juice and subsequent decantation the supernatants (M_c): $\mathrm{PWR} = \frac{M_c}{M_0} * 100\%$.

The AOC was determined by a modified oxygen radical absorbance capacity (ORAC) assay (Prior, Wu, & Schaich, 2005), as described by Bernaert et al. (2013). Analysis was performed in triplicate ($n = 3$) (Clariostar, BMG labtech, Ortenberg, Germany). Results were expressed in μmoles of Trolox equivalents per gram of dry weight (μmol TE·g^{-1} DW) and converted per gram fresh weight (μmol TE·g^{-1} FW) using both the moisture contents of wet and dry products (calculation and moisture contents in Supplementary data 4 & 5). The impact of the spiral-filter press on the AOC was evaluated by calculating the retention efficiency (% R). This represents the ratio of the AOC present after the process and before the process and is calculated by dividing the yield-corrected-AOC in JFO and PR by the AOC in MT. Also the juice and press residue extraction efficiencies were calculated (% E_{JFO} and % E_{PR}) representing the percentage of the AOC that ends up in the juice fraction or the press residue, respectively (calculation in Supplementary data 4).

Based on the generated knowledge and the resulting products, it was concluded that even under optimal conditions, no complete solid-liquid separation between juice on the one hand and peel and seeds on the other hand was achieved. This led to the investigation of an additional thermal pretreatment step.

2.2. Optimization of the thermal pretreatment

In order to obtain a better solid-liquid separation, a thermal pretreatment step was included in the biorefinery process (Fig. 1). From this point onwards, the optimization process was executed stepwise, using 75 kg of tomatoes per treatment. After each solid-liquid separation, an evaluation of the JY and the MC_{PR} was performed and a corresponding decision for the next set of conditions was taken.

A thermal pretreatment was performed by a mix/homogenize/emulgate system (UMSK 60 E, Stephan Food Service Equipment GmbH, Hamelin, Germany) wherein the mashed tomatoes were heated batchwise ($35\ \mathrm{kg \cdot batch^{-1}}$) and additionally milled under vacuum. This was performed in two steps. Initially, three temperatures were tested, based on cold and hot break used in conventional tomato processing (Goodman, Fawcett, & Barringer, 2002; Hayes et al., 1998; Heutink, 1986): 40 °C, 60 °C or 90 °C which were all applied for 3 or 6 min. Subsequently, the duration was varied (3, 6 or 9 min) for two temperature treatments (40 °C and 50 °C). The tomato mashes treated at 50 °C, 60 °C or 90 °C, were cooled down to 40 °C in order to generate a product with a constant temperature for subsequent application to the spiral-filter press. Subsequently, a solid-liquid separation of this thermally treated tomato mash (TT) was performed by means of the spiral-filter press using the same conditions as used in the optimized conditions in the first solid-liquid filtration (M, F, S, V) only varying the spirals (7-C (45°), 4-C (45°) and 4-C (38°)) in function of an optimal yield and a continuous operation.

2.3. Optimization of the second solid-liquid separation

The optimized system was tested to further refine the tomato matrix via a second solid-liquid separation of JFO, in order to obtain a tomato solids fraction (TS) and a less viscous juice filtered twice (JFT). Using JFO as an input stream means processing a very liquid product, conversely it was processed with the 3-C spiral (inclination angle 32°). The optimization included the testing of multiple filter sizes (100 μm, 80 μm and 60 μm) and multiple vacuum frequencies (0 Hz, 10 Hz and 50 Hz). F and S were kept constant at 15 Hz and 50 Hz, respectively.

2.4. Statistical analysis

A screening design was performed with four independent factors (S, V, M and C) to investigate their effect on the dependent variables JY, MC_{PR}, TH, TU and PWR. A contrast analysis was conducted in which the main effects and the first order interaction effects were estimated by means of the following first order linear regression model:

$$y = b_0 + b_1 \cdot s + b_2 \cdot v + b_3 \cdot m + b_4 \cdot c + b_5 \cdot sv + b_6 \cdot sm + b_7 \cdot sc + b_8 \cdot vm + b_9 \cdot vc + b_{10} \cdot mc$$

In this equation, the coefficients $b_{1 \rightarrow 4}$ represent the main effects of the corresponding factors, while the coefficients $b_{5 \rightarrow 10}$ describe the interaction effects of the factors. b_0 is the intercept and represents the grand mean of the dependent variable y. The coefficients represent half of the effects that are induced in the dependent variable upon changing the independent variable from a low to a high level. One-way analysis of variance (ANOVA) was conducted to identify effects with a level of significance of $p < 0.05$. Thereby, the best subset of independent variables was determined for each response function based on the Akaike information criterion (for finite sample sizes) which takes into account both model fit and complexity, obviating any overfitting problems. All statistical analyses of the optimization processes were performed with R 3.0.1 (R Foundation, Auckland, New Zealand). The AOC of the end products was statistically evaluated using ANOVA analysis followed by a Scheffé post-hoc test in SPSS Statistics 22 ($p < 0.05$). Sigmaplot 13 was used to visualize the data.

3. Results and discussion

3.1. Understanding the process impact of the independent variables during the first solid-liquid separation

Due to its economic importance at the processing plant, JY was used as a primary criterion to optimize the system. The higher the JY, the better the dewatering and the dryer the press residue. The JY-values, corresponding to the different experiments varied from 20.3% (exp. 3, Table 1) to 82.5% (exp. 16, Table 1), whereas reported tomato JY-values from a paddle or screw type extractor with hot break pretreatment range from 70 to 95% (Bates, Morris, & Crandall, 2001; Hayes et al., 1998; Min & Zhang, 2003). The large range in JY obtained throughout the experiment indicates a major effect of the system parameters. Fig. 2 shows the main effects and the interaction effects influencing the JY. From this figure, it can be concluded that the factors S, V and M all exert a significant positive effect on JY. The largest effects are ascribed to the spiral rotation frequency S. This positive effect can be explained by the tomato peel fraction that accumulates on the inner side of the sieve and blocks the pores. The rotating spiral can induce a scraping effect on the sieve thus removing the peel from the pores and increasing the juice extraction. It has to be noted that this effect is matrix dependent. In case of pear and apple for example, S exerts a negative influence on the juice yield, as S is also negatively correlated with the biomass residence time in the extraction cell (De Paepe et al., 2015a). The positive effect of V on JY can be explained by an extra extraction force as V is correlated with the underpressure in the extraction cell. Also M exerts a significantly positive effect on the JY, as increasing the pore size of the filter, allows juice to pass easier through the filter within the residence time. The choice of M will also influence the turbidity in the juice as more and larger particles are allowed to pass (Fig. 3), which will be discussed hereafter in more detail. Besides these three main effects also three significant interaction effects were identified. The positive V-M effect implies that the effect of the vacuum is higher when the filter pore size is enlarged. An explanation could be that the vacuum exerts a larger driving force on the juice through larger pores, as there is more "open space" to pull the liquid through. At smaller M, the juice is already

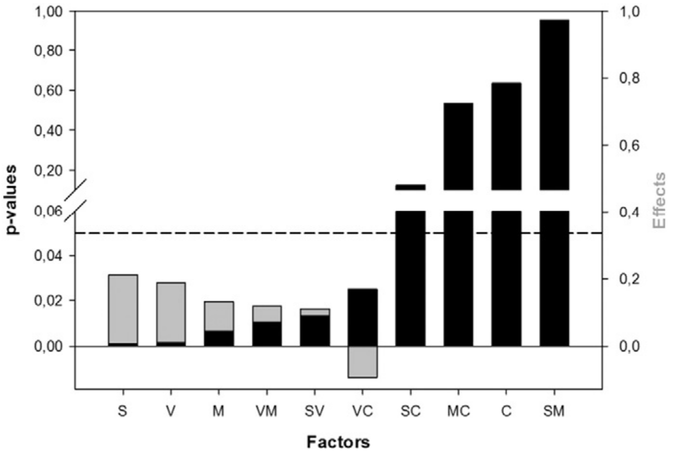

Fig. 2. Visualization of the significance and the magnitude of the effects of different factors (S, V, M, C and their interactions) on the juice yield. *P*-Values are represented by black bars and shown on the primary y-axis. The dotted line represents a *p*-value of 0.05 (95% significance level). The magnitude of the effects are represented by grey bars and shown on the secondary y-axis.

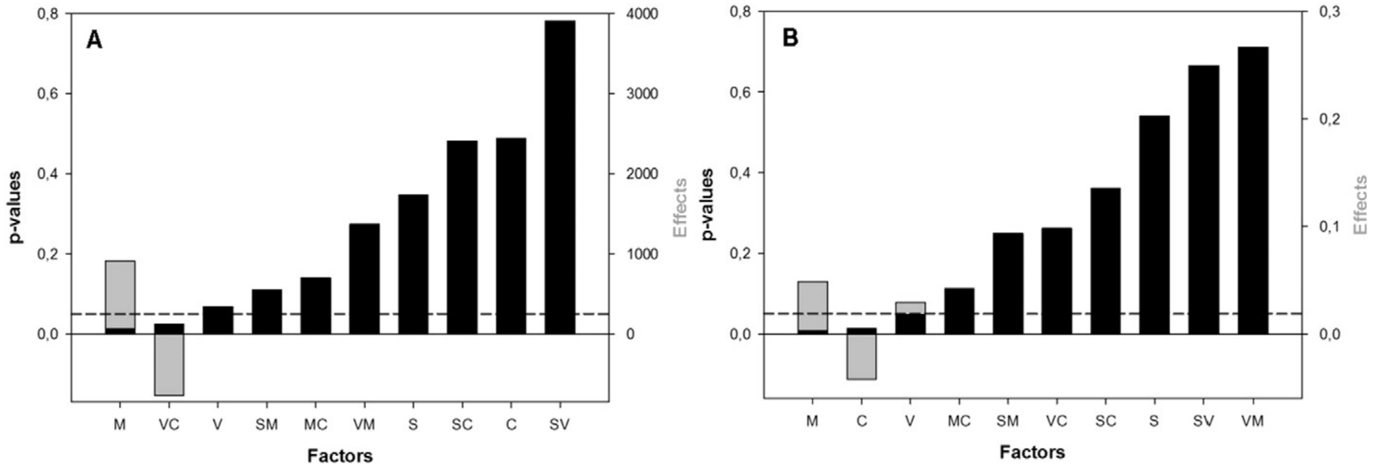

Fig. 3. Visualization of the significance and the magnitude of the effects of different factors (S, V, M, C and their interactions) on A) the turbidity (TU) and B) the precipitate weight ratio (PWR). *P*-Values are represented by black bars (primary y-axis). The dotted line represents a *p*-value of 0,05 (95% significance level). The magnitude of the effects are represented by grey bars and shown on the secondary y-axis.

blocked by the smaller pores and an increase of the vacuum can only offer a limited added-value. The positive interaction effect of V and S has a similar nature. The higher the frequency of the spiral, the more effect of V on the JY. Indeed, the higher S, the more the filter is scraped, the better the filter pores remain unblocked by particulate matter, hence the more juice can be extracted by increasing V. The V-C interaction effect is negative, implying that an increase of V will lead to a less pronounced increase in JY when C is high. This can be explained by the larger compression forces that are exerted on the material in a 7-C spiral. Increasing V will only lead to a small extra driving force on the JY in this system, which is already characterized by a high compression.

The JY can also be related to other dependent variables. The higher the JY, the better the solid-liquid separation and the lower the moisture content of the press residue. This inverse relation of MC_{PR} with JY is also visible in the significantly negative effects of S, V and M on MC_{PR} (results not shown). In each pressing system, the JY is related to the TH (Beveridge & Rao, 1997). In this experiment however, no significant factors nor interactions were found to influence TH. This could be caused by the soft tomato matrix for which only the feed pump frequency is determining the TH. As F is kept constant in this experiment, also constant TH values were found (475–498 $kg \cdot h^{-1}$). Increasing this F with regards to industrial scale systems, and maintaining the other process parameters might slightly decrease the juice yield but generally only in the order of 3–4%. This TH increase is limited however, as at a certain feed pump frequency, the system will "break-through". In that case, a parallel placement of identical extraction cells is needed. This implies a multiplication of the throughput by the number of extraction cells whereas the juice yield and juice quality remain constant, as also stated by De Paepe et al. (2015a). It has to be noted that the limiting technology to achieve higher throughput is often the milling technology instead of the juice pressing technology.

Values for TU varied from 3310 ± 40 NTU to 6965 ± 76 NTU in this experiment. These values are found to be only significantly influenced by the main effect of M and the interaction effect of V-C (Fig. 3A). M exerts a positive effect on the TU indicating that larger pore sizes, yield a more turbid juice, confirming the results obtained in pear juice production (De Paepe et al., 2015a). The interaction effect V-C has a negative origin, which means that using a vacuum has a larger effect on the TU when a 4-C spiral is used compared to a 7-C. This effect has also been seen on the JY and can be explained by the 7-C spiral system that already exerts a high compression force on the mashed tomatoes, leading only to a small extra driving force of V for extracting juice and small particles out of the mash. The high TU values can be attributed to the extraction of soft tomato tissue which collapses easily under pressure, creating cloud particles that contribute to the turbidity. In other presses, these cloud particles can clog juice escape channels and reduce the juice yield. Therefore press aids (such as rice hulls, ground wool pulp or shredded paper) are sometimes used to improve the press residue structure, a complex practice which can cause both economic and environmental damage (Beveridge & Rao, 1997). However, cloudy particles cause no problems in the spiral filter press, as the rotating spiral scrapes the solid material away from the filter pores, clearing the juice extraction channels.

Finally, a last parameter evaluated throughout the experiments is the PWR, referring to the water insoluble solids comprised of intact cells, broken cell walls and middle lamella compounds. This parameter has been found to correlate to the physical stability of the juice, where a higher PWR leads to less sedimentation and serum separation. Hence, the PWR is an important quality parameter for tomato derived products (Kaur, George, Deepa, Jaggi, & Kapoor, 2007). Experimental values varied between 20% and 33%, which are higher or at least within the same range compared to the values observed by Anthon and Barrett (2010). Fig. 3B shows that the PWR is significantly influenced by M, C and V. As can be expected, the larger the filter pore size, the more particles are found in the juice. The number of channels exerts a negative influence on PWR. In other words, the more channels present to compress the tomato mash, the more difficult particles are released to migrate to the juice fraction. Lastly, a significantly positive effect is found for the effect of V on PWR. Thus the higher the vacuum, the larger the driving force for juice extraction and the more sediment is drawn into the liquid fraction.

By means of the experimental screening experiment, it thus became clear that the studied parameters all show a JY optimum for a 4-C (45°) spiral operating with a large S, V and M, corresponding to experiment 16 (Table 1). These conditions were therefore chosen for the determination of the AOC of the end products.

3.2. Antioxidative capacity of the end products resulting from the first solid-liquid separation without thermal pretreatment

The low-oxygen spiral-filter press has already shown to impede oxidative degradation in the production of apple and pear juice, which is in part allocated to its extraction under low oxygen levels (De Paepe et al., 2015a, 2015b). In order to evaluate the process impact of the spiral-filter press during tomato juice production, samples resulting from the optimized first solid-liquid separation (exp. 16, Table 1) were analyzed for their antioxidant capacity. The AOC's of the end products (JFO and PR) were therefore compared to the AOC of the input product (MT), in order to calculate the spiral-filter press process impact on the AOC.

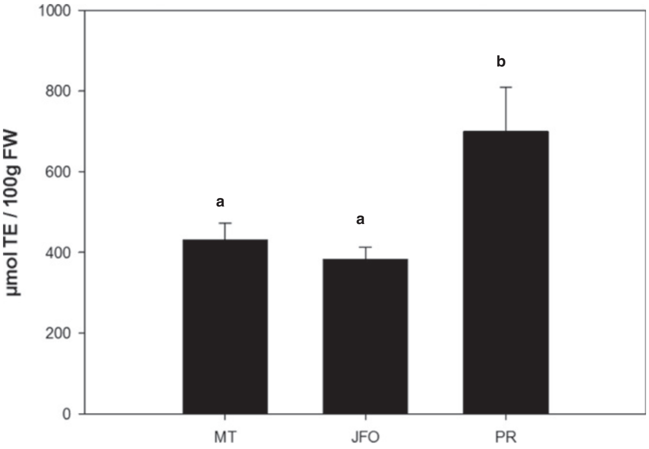

Fig. 4. ORAC values (μmol TE/100 g FW) of the different fractions obtained after solid-liquid separation ($n = 3$).

The ORAC values of the three fractions resulting from the optimized solid-liquid separation are depicted on a fresh weight basis in Fig. 4 (calculation and moisture contents in supplementary data 4 & 5). Here, it is shown that there was no significant decrease in AOC in juice compared to fresh fruit. Furthermore, the PR was characterized by a significantly ($p < 0.001$) higher AOC compared to the other two fractions. This is confirmed in Toor and Savage (2005) who separated tomatoes in different fractions (skin, pulp and seeds) and subsequently determined their individual AOC.

The ORAC values of MT were in the same order of magnitude compared to reported ORAC values for raw tomatoes. The USDA database reports ORAC values for raw tomato ranging between 216 and 457 μmol $TE \cdot 100\ g^{-1}$ FW (Haytowitz & Bhagwat, 2010). Also the results of Ou, Huang, Hampsch-Woodill, Flanagan, and Deemer (2002) and Zhou and Yu (2006) are within the same range. The large fluctuations in the reported ORAC values can be ascribed to a dependency on variety, ripening stage, location and harvesting season (Ou et al., 2002). This stresses the importance of evaluating AOC's within the process relative to the input product, when evaluating process impact. The relative change of the AOC throughout processing was calculated by means of the retention efficiency (% R). An % R-value of 102 ± 12% showed that the yield-corrected-sum of the ORAC values of JFO and PR, expressed on the basis of their actual weight fraction, equalled the ORAC value of MT. This implies a conservation of the AOC which could be related to the use of the low-oxygen spiral-filter press, preventing oxidative degradation. Furthermore, also an insight was gained in the distribution of the AOC within the three products. Despite its small volume (17.5%), the press residue was found to contribute 28 ± 5% to the total ORAC value of the tomato. This shows the potential value of this so-called waste fraction and confirms the relevance of designing a biorefinery system where these fractions can also be valorized.

These results however have to be interpreted carefully as the AOC does not reflect individual antioxidative compound shifts (Martínez-Valverde, Periago, Provan, & Chesson, 2002). Therefore, in order to gain more insight in the impact of the spiral-filter press on the chemical composition of the end-products, a multifaceted approach is necessary where additional investigations of the individual antioxidative compounds are performed. Therefore, detailed investigation of the obtained fractions using LC-MS analysis for determination of phenolics and carotenoids and titrimetric measurements for determination of vitamin C are subject of further investigation.

3.3. Optimization of the pretreatment

The best case in the previous optimization resulted in a 82.5% juice yield and a press residue with a moisture content of 90.1 ± 0.17%. However, it was visually determined that the solid-liquid separation was not completely carried out, as the press residue still contained tomato flesh and juice. An inherent consequence from this incomplete solid-liquid separation, was a press residue that was not separable in a homogeneous seeds and peel fraction. This was due to the tomato flesh fraction that interfered with a flotation-sedimentation process which was used to separate seeds and peel. As a result, biobased product development starting from pure seeds and/or peel fractions was hindered. The seeds have the potential to produce vegetable oil as an ingredient in food or cosmetic products whereas the peels can serve as a feedstock for carotenoid extraction (Alvarez & Rodríguez, 2000; Eller, Moser, Kenar, & Taylor, 2010; Schieber et al., 2001). The combination of both factors led to the conclusion that a thermal pretreatment was necessary, as often applied in industry (Hayes et al., 1998).

In the first explorative thermal pretreatment experiment, three temperatures (40 °C, 60 °C and 90 °C) were tested for 3 and 6 min (results not shown). The two highest temperatures are often applied in industrial tomato processing using cold and hot break (Goodman et al., 2002). However, a lower temperature (40 °C) was also included in the experiment as it is known that elevated temperatures can alter the flavor, color and nutritional quality of the juice (Min & Zhang, 2003; Sánchez-Moreno, Plaza, de Ancos, & Cano, 2006). The choice of the spiral of the following solid-liquid separation was reconsidered since the consistency of the input material changed compared to the non-thermally treated tomato mash. Explorative experiments showed that a 7-C spiral performed better on thermally pretreated material. Solid-liquid separation (7-C (45°)) of these pretreated mashes all resulted in juice yields significantly larger than 82.5%, indicating that the introduction of a thermal treatment indeed led to a significant increase in the extent of solid-liquid separation. No significant differences were however observed in the JY and MC_{PR} between the different combinations. Furthermore, an ad hoc sensory evaluation showed that the juices smelled and tasted more "cooked" at higher temperatures. Therefore, an additional experiment was conducted at two lower temperatures (40 °C and 50 °C) for 3, 6 and 9 min, in order to investigate if a longer treatment could lead to a higher extent of solid-liquid separation. The resulting juice yields and moisture contents of the press residues are shown in Table 2. Here, also the conditions, leading to the highest yield in the non-thermally treated experiments were added as reference.

From this experiment, it can be concluded that applying a thermal treatment led to a significant increase in JY and a significant decrease in MC ($p < 0.001$). However between the thermal treatments, no significant effect of temperature nor time was found. This implies that applying a heat treatment is sufficient to detach the peel from the flesh, independent of the duration or the temperature of the heat treatment. Consequently, the minimum temperature-duration combination (40 °C – 3 min) was selected in order to affect the quality of the tomato product as little as possible, yet obtaining a thorough solid-liquid separation. However, due to the larger compression forces in the 7-C spiral, a compression build-up was often encountered, due to an increasingly dry press residue, which resulted in system blocking. Therefore, the 4-C spiral with inclination angle of 38° was selected for further operation. Although resulting in a slightly lower juice yield (97.0%), it was able to work on a continuous basis. The choice of 38°

Table 2
Time and temperature of the applied thermal pretreatments and the corresponding juice yields (JY) and moisture contents of the press residue (MC_{PR}) using a 7-C (45°) spiral.

Time (min)	Temperature (°C)	JY (%)	MC_{PR} (%)
0	0	82.5	90.1
3	40	98.2	70.5
6	40	98.7	62.5
9	40	98.7	60.4
3	50	98.5	61.0
6	50	98.5	69.5
9	50	98.7	62.8

instead of 45°, as optimized in the first-solid-liquid separation, can be explained by the fact that the more liquid products are less susceptible to compression, which consequently implies that an increased steepness of the channels (45° versus 38°) does not generate any extra driving force. What is more, less steep channels lead to an increased residence time of the tomato mash in the extraction cell, thereby improving the juice extraction (De Paepe et al., 2015a).

Using the proposed thermal pretreatment enabled the production of a press residue that consisted solely out of peel and seeds, which allowed their further separation and valorization (Supplementary data 6).

3.4. Optimization of the second solid-liquid separation

Further refinement of the tomato was investigated by stripping the TS fraction from the viscous JFO leading to a less viscous JFT and a TS fraction with a firm puree texture. From the results of the first solid-liquid separation, it became clear that juice yield was predominantly determined by S, V and M. The input stream JFO was more liquid compared to both input streams MT and TT from the previous experiments. In general, thermally treated mashes are difficult to process using conventional pressing technologies as they tend to slide through the press cloth or block the pores leading to very low juice yields, often <50% (Beveridge & Rao, 1997). The spiral-filter press is however able to process these liquid streams and based on the conclusions drawn above on the low compressibility of the liquid biomass, a 3-C spiral with small inclination angle (32°) was used for optimal yield. Subsequently, vacuum and filter pore size were optimized. In the first experiment a filter pore size of 60 μm was used and three different vacuums were tested (0 Hz, 10 Hz and 50 Hz). Here, it was concluded that a higher vacuum led to less TS fraction with a more solid structure. In the extreme condition of 50 Hz vacuum, even the whole input stream was pulled through the filter, exiting the system at the juice side. The vacuum thus exerted a too large extraction force. When applying no vacuum, the whole input stream tended to exit the system at the press residue side. A smaller vacuum (10 Hz) therefore appeared to be optimal. Finally, the two filter sizes (80 μm and 60 μm) were compared. In the first case, almost no TS were extracted from JFO (TS yield 4.2% ± 0.9%). Due to the larger pore size, more small particles that otherwise would end up in the TS fraction, passed through the filter and ended up in the JFT fraction. Using the 60 μm filter led to more TS mass (TS yield 8.9% ± 0.9%). On the one hand, this could be allocated to the fraction of small particles (theoretically between 60 μm and 80 μm) that were not allowed to pass the 60 μm filter and thus ended up in the TS fraction. On the other hand, it could be caused by a larger fraction of tomato juice, that could theoretically pass the filter pores, but of which the flow was obstructed by the small pore size. The choice of this filter should be made in function of the aimed application: smaller amounts of less liquid TS could be obtained using a 80 μm filter, whereas a 60 μm filter could generate a larger TS-mass with a slightly smaller dry weight content. Besides being flexible towards the biomass input, the spiral-filter press is thus also able to produce a variety of textures in its end-products (juice, smoothie, puree), which is further investigated in part II of this study.

4. Conclusion

The spiral-filter press is proposed in the context of food losses as a promising technology, able to adequately refine a variety of biomass matrices, facilitating the valorization of all the obtained fractions. Using tomato as a model crop, a robust refinery process was developed, consisting of a light thermal pretreatment (40 °C, 3 min) followed by a spiral-filter pressing which proves to be flexible towards input biomass as well as adjustable in function of the desired generated end-product (juice, smoothie, puree). Generally applicable insights in the working of the spiral-filter press were obtained by elucidating the effects of different process parameters on the juice yield and juice quality parameters (turbidity, precipitate weight ratio). These results are crucial for further product formulation and process design of biomass with a similar soft texture, and can be easily scaled to larger systems by increasing the feed pump frequency or parallel placement of identical extraction cells. Furthermore, the research suggests that the spiral-filter press is a qualitative technique, able to conserve the antioxidative potential of the raw tomato (102 ± 12%) during pressing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ifset.2016.10.005.

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