Twin-screw extrusion technology for vegetable oil extraction: A review

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A B S T R A C T

Vegetable oils present a valuable class of bioresources with applications in both food and non-food industries and a production that has been steadily increasing over the past twenty years. Their extraction from oilseeds is a key process, as it exerts a strong impact on the resulting oil characteristics and quality. In view of the recent pressure towards sustainability, oilseed processing industries are taking renewed interest in thermomechanical pressing as a means to obtain high quality oils. This work focuses on twin-screw extrusion for vegetable oil extraction and reviews recent technological advancements and research challenges for the design and optimization of novel oil extraction processes. It comprises a critical analysis of the application of twin-screw extruders against their more conventional single-screw counterparts. Further, a comprehensive overview of the key parameters influencing the process performance is provided, while considerable attention is given to the development of innovative green extraction processes using twin-screw extrusion.

Keywords:
Twin-screw extrusion
Vegetable oil extraction
Thermomechanical pressing
Press cake
Oilseed processing

Contents

1. Introduction

Recent environmental concerns and the steady depletion of fossil resources have led to the increasing implementation of renewable resources and sustainable processing in industry. With a global annual production of 174 million tons in 2013–2015 and a market comprising both the food and the non-food industry, vegetable oils present a valuable class of such bioresources (OECD/FAO, 2016). In industry, the most commonly applied oil extraction process for seeds with relatively high oil content, i.e. more than 20%, comprises both a pre-pressing step and a solvent extraction step in order to attain high oil recoveries. Traditionally, pre-pressing was conducted by the use of a hydraulic press in batch operation. Since the mid-20th century, however, single-screw presses are most commonly applied in industrial practices for mechanical oilseed pressing, as they allow continuous operation. When compared to solvent extraction, full mechanical pressing of oilseeds results in a significantly lower oil yield. However,

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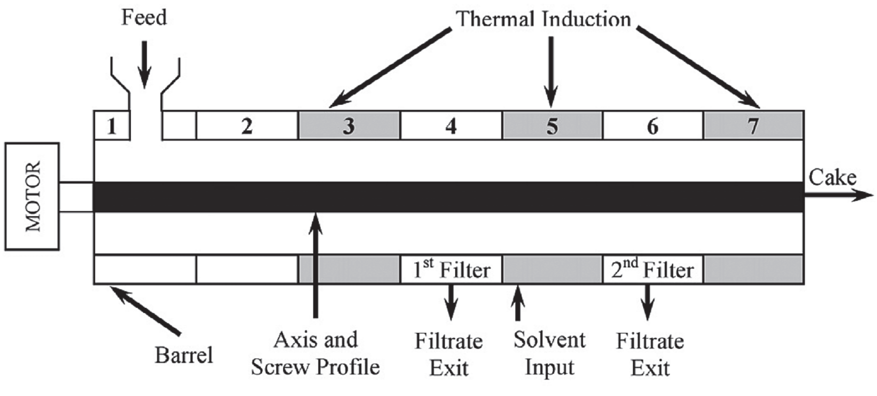
environmental and health concerns associated with the use of hazardous solvents such as *n*-hexane, as well as economic considerations regarding energy consumption and waste production, have led to a resurgence of interest in mechanical pressing as a sole means to the continuous extraction of vegetable oil. Next to this, there is a niche, high-value market for natural vegetable oils that have not been in contact with any solvents or chemicals, particularly for the food and cosmetics industry. Twin-screw extrusion presents an innovative technology with increasing applications in the polymer industry, the cereal industry, the pet food industry and the paper industry. Even though it is currently not yet applied in the oilseed processing industry, it may present a promising technique for sustainable vegetable oil extraction. Therefore, it has been increasingly applied to achieve efficient oil extraction from various oilseeds (Dufaure et al., 1999b; Evon et al., 2013; Isobe et al., 1992; Kartika et al., 2006, 2010; Li et al., 2007; Uitterhaegen et al., 2015) and even from the whole sunflower plant (Evon et al. 2010a, 2016). This review aims to provide a clear and concise overview of recent research focusing on twin-screw extrusion technology as a means for vegetable oil extraction. Particular focus will lie on the technological advancements that have been made and the research challenges that are encountered during the design and optimization of novel oil extraction processes. This comprises the recovery of vegetable oil through thermomechanical extrusion-pressing, as well as through extrusion processes applying green solvent-assisted extraction techniques. It will be restricted to twin-screw extrusion, as hydraulic pressing, as well as single-screw extrusion-pressing, have been extensively described elsewhere (Lanoisellé and Bouvier, 1994; Savoire et al., 2013).

2. Twin-screw extrusion technology

The first fully intermeshing, co-rotating twin-screw extruder, then referred to as a malaxator, was developed by Coignet in 1869 for the concrete industry (1869). Specific designs of twin-screw extruders for the pressing of oilseeds were developed in the 1990s, a process that was mainly driven by extruder manufacturers (Bouvier and Guyomard, 1996). These extruders consist of two intermeshing, co-rotating or counter-rotating screws mounted on splined shafts and enclosed in a modular barrel. The specificity of a twin-screw extruder-press lies in the installation of a filtration module, allowing the collection of a liquid filtrate expelled from the material by compression. The intermeshing, co-rotating twin-screw design enables the extruder to operate as a positive displacement pump, resulting in a throughput that is independent from the screw speed and pressure and ensuring efficient mixing and heat transfer (Bouvier and Campanella, 2014). A design with intermeshing, counter-rotating screws generates longer retention times and high pressure and shear at the upper intermeshing zone of the screws, leading to intensive mechanical treatment of the material (Isobe et al., 1992). The modular screw-barrel assembly shows important processing advantages, as the configuration of segmented worm screw elements allows a wide variation of the screw profile and the presence of different operating sections in the same extruder. An example of such advanced process design is presented by Kartika et al. for sunflower oil extraction (2010), where sunflower seeds were subjected to thermomechanical pressing and subsequent green solvent extraction in one twin-screw extruder equipped with two filtration modules and an intermediate solvent pump. A schematic representation of the extruder configuration and the screw profile is presented in Fig. 1. The diversity of available screw designs results in the extensive capability to vary the extruder screw configuration. A first type of screw elements consists of elements with a right-handed pitch, which ensure consistent conveying of material and show a high pumping capacity. Depending on the pitch and the amount of flights, these elements are applied in the feed or compression section of the extruder. Screw elements showing a left-handed pitch, often referred to as reverse screw elements, form a second type of elements and exert a transportation force on the material that is opposite to the flow direction, causing intense shearing. In particular, the combination of conveying and successive reverse screw elements positioned near a filtration element results in the effective compression of material, forming a dynamic plug, and a good L/S separation due to an efficient pressure buildup (Dufaure et al., 1999a; Uitterhaegen et al., 2015). Consequently, this pressing zone inside the twin-screw extruder barrel allows the effective expression of vegetable oil, which may be collected through the



1		2		3				4			5		6		7			
T2F 66	C2F 50	C2F 33	DM 10x10	C2F 25	BB 5x5	C2F 33	BB 5x5	C1F 25	C1F 15	CF1C-15	C1F 33	C1F 33	C1F 33	C1F 25	CF1C-25	C1F 25	CF1C-25	C1F 25

Fig. 1. Schematic representation of the Clextral BC45 twin-screw extruder configuration and the screw profile applied for sunflower oil extraction through combined thermo-mechanical pressing and solvent extraction (Kartika et al., 2010). T2F, trapezoidal double-flight screw; C2F, conveying double-flight screw; C1F, conveying single-flight screw; DM, monolobe paddles; BB, bilobe paddles; CF1C, cut flight, single-flight reverse screw. The numbers following the type of screw indicate the pitch of T2F, C2F, C1F, and CF1C screws and the length of DM and BB paddles.

filter element. Finally, blocks of monolobe or bilobe paddles may be included and constitute a trituration zone in the extruder, providing intensive crushing of the material and facilitating oil expression through the rupture of cell structures. The high variability in screw configuration allows fine-tuning of the pressure profile inside the extruder and local shear-time-temperature histories of the resulting products, which are important factors for respectively the oil extraction efficiency and the oil and press cake quality.

3. Twin-screw extrusion versus single-screw extrusion

Contrary to single-screw extrusion, twin-screw extrusion technology is currently not widely employed on an industrial scale for the mechanical pressing of oilseeds. However, this innovative technology may present some interesting advantages when compared to its more traditional single-screw counterpart. In a single-screw extruder, the material is conveyed along the screw axis only through friction with the barrel wall, while a flow restriction at the extruder outlet causes a pressure gradient that induces a pressure flow opposite to the material flow. The combination of both flows determines the feed rate and therefore, in the case of single-screw extrusion, the extruder throughput is dependent on the screw speed (Bouvier and Campanella, 2014). Furthermore, with friction as the main factor, single-screw extrusion can be high energy-consuming and, in combination with its poor mixing capacity, this can lead to overheating and subsequent oil and cake quality deterioration (Singh and Bargale, 2000; Uitterhaegen et al., 2015). Twin-screw extrusion, on the other hand, acts as a positive displacement pump owing to the intermeshing behavior of the co-rotating screws. Thus, during operation, a large part of the channel is not completely filled (Janssen, 1989). This leads to the fact that for twin-screw extruders, the process throughput is independent of the pressure profile and screw speed, resulting in a higher process flexibility (Harper, 1989). Next to this, twin-screw extrusion shows substantially improved mixing and a high level of micromixing due to the interpenetration of the screws and the ability to introduce mixing blocks along the screw profile, which in turn leads to an enhanced heat transfer and product uniformity (Bouvier and Campanella, 2014; Dziezak, 1989). These key characteristics of twin-screw extrusion allow a thermomechanical treatment of the oilseeds in different operating sections, thereby eliminating the necessity of commonly applied seed pre-treatment steps such as cooking, drying or flaking (Savoire et al., 2013). Many studies have shown that these pre-treatments are of key importance in single-screw pressing operations to achieve satisfactory oil yields but are often high energy-consuming and thus costly processing steps and may furthermore exert a negative impact on the obtained oil quality (Evangelista and Cermak, 2007; Singh et al., 2002; Soetaredjo et al., 2008). Advantages of single-screw extrusion over twin-screw extrusion include its simpler operation and reduced capital cost, the latter being up to twice as high for twin-screw extruders (Riaz, 2000). However, when considering operational costs, twin-screw extrusion may present some important economic advantages. It is capable of introducing a significantly higher mechanical energy input, whereas single-screw extruders require a higher thermal input to compensate for this limitation, leading to their higher energy consumption (Bouvier and Campanella, 2014; Harper, 1989). This has been demonstrated for the mechanical pressing of camellia (Li et al., 2014) and jatropha seeds (Evon et al., 2013), where twin-screw extrusion resulted in an energy saving of 40% and 80%, respectively, when compared to single-screw extrusion. The high flexibility and productivity inherent to twin-screw extrusion further exerts a positive impact on the economic feasibility of the process. This is in contrast to single-screw extrusion, where the industrial presses are most often specifically designed for a single oilseed species. Furthermore, the simultaneous augmentation of the process capacity, the oil flow rate and the extraction efficiency is usually not possible for single-screw extrusion, as an increased pressing efficiency through higher pressures inside the extruder comes at the expense of the process throughput (Savoire et al., 2013). This results in important restrictions in terms of process optimization, which, as a result, will depend upon whether one seeks to obtain a low residual oil content of the press cake or a high process capacity.

4. Thermomechanical pressing through twin-screw extrusion

Given its processing advantages and versatility, an increasing number of studies have recently been conducted on vegetable oil extraction using twin-screw extrusion technology. This section aims to present an overview of research efforts that have been made on the development and optimization of thermomechanical oilseed pressing processes using twin-screw extrusion. Most studies have reported the effect of the screw configuration and process parameters such as the extrusion temperature, the screw speed and the feed rate, on the process performance, i.e. the oil extraction efficiency. Effective mechanical pressing, i.e. with adequate pressure build up and L/S separation to obtain a liquid filtrate, for vegetable oil extraction using a twin-screw extruder has been executed for rapeseed (Li et al., 2007), sunflower seeds (Dufaure et al., 1999a; Isobe et al., 1992; Kartika et al., 2005, 2006), coriander seeds (Sriti et al., 2012; Uitterhaegen et al., 2015), jatropha seeds (Evon et al., 2013), camellia seeds (Li et al., 2014), and Pongamia pinnata seeds (Amruthraj et al., 2014).

4.1. Twin-screw extruder-press design

Several studies focusing on the design of a twin-screw extruder for the mechanical pressing of oilseeds have compared the resulting process performance to that of a single-screw extruder-press. Isobe et al. (1992) reported one of the first twin-screw press designs and used dehulled sunflower seeds as a model oilseed. The design consists of a pilot-scale partially intermeshing, counter-rotating twin-screw extruder-press with a barrel composed of vertical, parallel plates varying in diameter. The twin-screw press operated at a feeding rate of 50–58 kg/h and attained a high oil recovery of 94% for dehulled sunflower seeds. The process was compared to a lab-scale single-screw pressing operation with a feed rate of 19–23 kg/h, which resulted in a low oil recovery of 20%. Care must be taken, however, in comparing these process performances, as they operate on a significantly different production scale. Nonetheless, the generally observed trend in the scale-up of a thermomechanical pressing process for oil extraction is a decrease in the extraction efficiency with an increasing scale of production. As an illustration, a decrease in oil recovery from 82 to 62% was found during the thermomechanical pressing of sunflower seeds using a twin-screw extruder of increasing volume and an increased feed rate from 14 to 22 kg/h, respectively, while maintaining the raw material characteristics and operating conditions (Dufaure et al., 1999a). Therefore, it may be carefully stated that the twin-screw process described by Isobe et al. (1992) and showing an increased oil recovery, as well as a larger production scale, has a superior process performance as compared to the lab-scale single-screw operation. A low single-screw pressing efficiency for dehulled seeds has been described by several authors and has been attributed to the vastly reduced level of friction that is induced by these seeds due to the absence of the fibrous hulls and further due to their significantly increased oil content, showing a lubricating effect inside the extruder (Isobe et al., 1992; Li et al. 2007, 2014). In terms of energy consumption, twin-screw pressing of dehulled sunflower seeds resulted in a 9 times reduction of the specific mechanical energy (0.14 kW·h/kg oil, versus 1.25 kW·h/kg oil for single-screw extrusion), rendering the process much more energy efficient (Isobe et al., 1992). However, the latter comparison should be considered with caution in view of the difference in production scale of both processes. The processing of dehulled seeds with a high pressing efficiency further results in an important increase in the oil productivity, as the feed flow shows a significantly higher oil content. The authors further highlighted that the sunflower kernels were not subjected to any mechanical or thermal pre-treatment and that the designed twin-screw press was effective in replacing each step of the commonly conducted pre-treatment processes. Another counter-rotating twin-screw press design was developed by Amruthraj et al. (2014) in order to meet a production rate of 80–100 kg/h. Two different barrel configurations were considered, the first being designed specifically for an efficient pressing of Pongamia pinnata seeds with mass production at a low cost, while for the second configuration, high process flexibility was pursued for research and development purposes using a variety of different seeds. Both barrels were equipped with liners composed of square bars to allow the expression and recovery of vegetable oil through the gaps in between adjacent blades. Pilot-scale cold pressing processes using an intermeshing, counter-rotating twin-screw extruder were successfully developed for dehulled rapeseed (Li et al., 2007) and dehulled camellia seeds (Li et al., 2014). Cold pressing of dehulled oilseeds can result in vegetable oil and press cake with improved quality characteristics, as high temperatures may induce off-flavors and darkening of the oil, as well as the degradation of thermosensitive minor components. It was shown that nutritional and functional compounds, such as tocols and phytosterols, were more efficiently extracted using a twin-screw cold pressing process when compared to a traditional single-screw pre-pressing process. For example, when applying a twin-screw cold pressing process to extract camellia oil, the vitamin E content was found 2.6 times higher and the unsaponifiable matter had doubled compared a single-screw pre-pressing operation (Li et al., 2014). At the same time, the press cake was of greater nutritional value with doubling of the crude protein, soluble sugar and starch content, while the amount of crude fiber had reduced by 55%, rendering it more valuable for the feed industry. For camellia seeds, the economic feasibility of the process with a capacity of 30 tons/day was verified and an energy saving of 30–40% could be achieved with the twin-screw process when compared to the single-screw process (Li et al., 2014). The first application of a co-rotating twin-screw extruder for the mechanical pressing of oilseeds was described in 1996 by Bouvier and Guyomard (1996). The extruder design is presented in Fig. 2 and comprises two different sections. The first section involves co-rotating and co-penetration twin screws with elements of varying pitch and reverse screw elements to create a pressure build up and express oil. The second section is composed of two co-rotating single screws of increasing diameter and decreasing pitch. As such, both sections show the presence of a pressing zone and are equipped with a filtration element, represented in Fig. 2A by vertical bars in the extruder barrel, for the recovery of the expressed oil. With this configuration, a high oil extraction efficiency of between 81 and 85% and between 85 and 90% was found for the pressing of rapeseed and sunflower seeds, respectively, at a feed flow rate of 70 kg/h (Bouvier and Guyomard, 1996). The principle of two separate filtration zones for two consecutive pressing stages was also applied by Kartika et al. (2006) for the pressing of sunflower seeds, although only one filtration element led to an effective L/S separation and the recovery of a filtrate.

Many studies have shown the key importance of the screw configuration on the extrusion process performance, its energy consumption and the obtained product quality (Dufaure et al., 1999a; Evon et al., 2013; Gautam and Choudhury, 1999a, 1999b; Kartika et al., 2005; Kartika et al. 2006). Most research focuses on the pressing zone, in particular the length, positioning, spacing and the pitch of the reverse screw elements, while some experimental work has also been conducted to enhance the trituration zone, which often involves kneading elements. The position of the reverse screw elements relative to the filtration module exerts a high influence on the oil extraction efficiency of the process. It was demonstrated for both coriander seeds and jatropha seeds that when the reverse screw elements were placed further downstream the screw axis, rather than immediately after the filter element, the pressing capacity and energy consumption of the extrusion process was significantly lower (Evon et al., 2013; Uitterhaegen et al., 2015). The authors highlight the presence of a significant oil loss due to the accumulation of oil between the pressing and the filtration zone, where it was prevented from draining freely. Spacing of the reverse screw elements, i.e. the positioning of a forward conveying

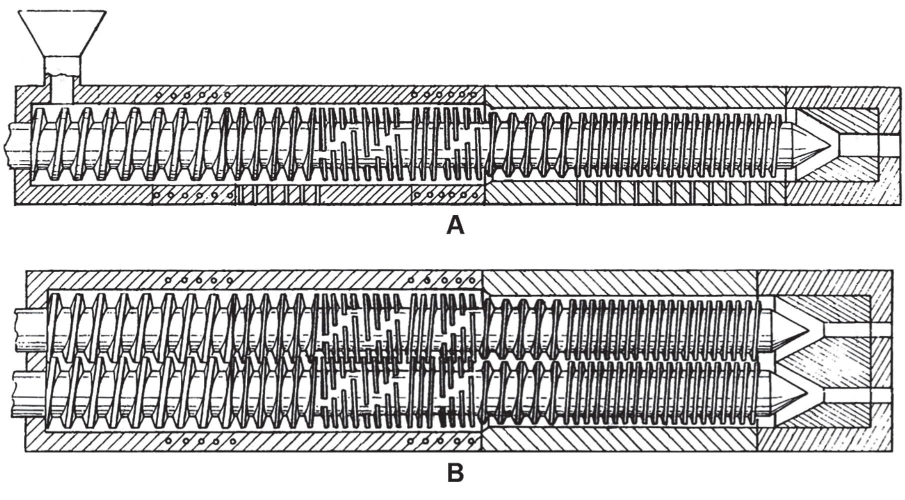


Fig. 2. Schematic representation of the twin-screw extruder design comprising two different pressing sections and developed by Bouvier and Guyomard for the thermomechanical pressing of oilseeds (Bouvier and Guyomard, 1996). A. Schematic view through a vertical plane running through one of the screw axes; B. Schematic view through a transversal plane showing both screw axes.

screw elements in between two reverse screw elements, was shown highly effective as a means for increasing the extraction efficiency of the mechanical pressing process of sunflower seeds (Kartika et al., 2005, 2006). This particular screw configuration results in a greater degree of fill of the extruder and consequently a higher mechanical energy input, while it enhances the compressing action of the reverse screw elements. Next to this, it creates an expanded material structure, which is easily ruptured upon high shear stress, facilitating the diffusion of oil droplets through the fibrous matrix and to the material surface and the filter (Kartika et al., 2005, 2006). Spacing of the reverse screw elements has also been shown to increase the residence time of material in the extruder, which is an important intermediate process parameter (Gautam and Choudhury, 1999b; Gogoi et al., 1996). The importance of residence time for the extrusion pressing process lies in the fact that the flow of oil through the porous matrix of fibrous material, which is further restricted due to the high level of compression, is a time-dependent process (Bargale et al., 1999). Further fine-tuning of the pressing zone of a twin-screw extruder-press can be carried out through modifications of the length and the pitch of the reverse screw elements. With the application of reverse screw elements of an increased length or a lower pitch, a higher degree of fill of the extruder is obtained, leading to an improved pressing efficiency due to the enhanced pressure buildup and longer residence time of the material inside the extruder (Dufaure et al., 1999a; Evon et al., 2013; Gautam and Choudhury, 1999a; Isobe et al., 1992; Prat et al., 1999). The increase in counter-pressure further leads to an increased energy consumption of the extruder motor and an intensified self-heating of the material due to friction (Dufaure et al., 1999a; Gautam and Choudhury, 1999b). This increase in friction and energy consumption is further intensified by the decreased residual oil content of the press cake, considering the lubricating effect of vegetable oil in the extruder (Evangelista, 2009). However, as the increased extruder energy consumption is accompanied by an increase in oil recovery, the specific mechanical energy in terms of energy consumption per unit of oil produced often decreases with an enhanced pressing intensity, resulting in a more economically favorable pressing process. It is important to note, however, that there is a practical limit to increasing the flow restriction and consequently the pressure buildup in the pressing zone. The use of reverse screw elements with a reduced pitch for the pressing of sunflower seeds led to an enhanced oil extraction and a lower cake residual oil content, but also resulted in a strong increase in the filtrate solids loading (the foot content) (Kartika et al., 2005). This increase could be explained by an excessive degree of fill and the accumulation of solid particles upstream from the pressing zone and thus near the filtration module. As a consequence, an important oil loss was encountered during centrifugation and the resulting oil yield was reduced. When the reverse screw elements are too restrictive, they may even completely inhibit the transport of material and thus the extrusion process (Prat et al., 1999). Uitterhaegen et al. (2015) have observed this phenomenon for the twin-screw pressing of coriander fruits, where reverse screw elements with a −25 mm pitch induced an excessive filling of the extruder, leading to blocking of the sieve openings in the filtration module by solid particles and thus preventing oil from draining freely. Furthermore, such configuration led to a strong increase in the extruder motor torque, up to the point where it exceeded the torque limit, resulting in an emergency stop of the machine. A similar situation was encountered during the pressing of jatropha seeds, where the use of reverse screws of increased length required a concurrent increase of the screw speed, which decreases the degree of fill, in order to avoid blocking of the extruder (Evon et al., 2013).

Next to the pressing zone, most often involving reverse screw elements, researchers have focused on the configuration of the trituration zone of a twin-screw extruder-press, which is usually composed of one or several blocks of kneading elements, in particular monolobe and/or bilobe paddles. The kneading elements can be positioned with different staggering angles in order to adjust their mixing and flow restricting action. The lower the staggering angle, the higher the conveying action of the kneading block, while a neutral 90° staggering angle shows no conveying action and maximal distributive and dispersive mixing (Bouvier and Campanella, 2014). Dufaure et al. (1999a) reported the effect of the configuration of the trituration zone on the efficiency of oil extraction from sunflower seeds. Two series of bilobe paddles were installed with a 45° staggering angle, which ensured thorough crushing and shearing of the material and consequently its cell rupture. The addition of a set of monolobe paddles at 45° just upstream from the filtration module was found to complement the effect of the bilobe paddles and enhance the oil extraction efficiency. This favorable effect on oil extraction was attributed to the radial compression exerted by the monolobe paddles on the material, facilitating the diffusion of oil droplets through the fibrous matrix. This configuration was further optimized by Kartika et al. (2005), who reported that the positioning of the monolobe paddles in between the two sets of bilobe paddles and the reduction of the interval between the mixing blocks, resulted in an increased shearing action of the trituration zone and thus an enhanced oil recovery. Like for the flow-restricting action of the reverse screw elements, there is a practical limit to the crushing action of the kneading blocks in the trituration zone. During the mechanical pressing of jatropha seeds, it was found that a combination of one set of monolobe paddles at a 45° angle and two sets of bilobe paddles at a 90° angle, the latter exerting a strong crushing and shearing action, resulted in an excessive size reduction of the solid particles (Evon et al., 2013). This led to important filtrate foot contents of at least 56%, as the small particles were easily driven through the filter element. Several research studies have reported the presence of large amounts of foot in the filtrate, in particular when compared to the commonly obtained low foot contents in single-screw extruder filtrates (Evon et al., 2013; Sriti et al., 2012). This excessive solids loading results from the strong crushing and shearing capacity of the modular twin-screw profile. Next to the rupture of cell structures and thus the enhancement of the oil expression, it also results in a very strong particle size reduction of the material, allowing an easy passage of small particles through the filter element. High foot contents in the obtained extrusion filtrates often lead to substantial oil losses through the subsequent centrifugation, as the solid particles will still enclose a large amount of oil. In industrial practices, the foot is often reintroduced at the extruder inlet in order to minimize oil losses. This, however, creates an additional feed flow and in the case of important filtrate foot contents, it may result in the instability, as well as a reduced capacity, of the extrusion process. Several researchers have suggested the use of a filtration module with smaller sieve openings in order to reduce the foot content of the filtrate (Evon et al., 2013; Uitterhaegen et al., 2015). However, as most filtration modules applied for twin-screw extruder-presses already comprise sieve openings with a 500 μm diameter, the manufacture of a filtration element with smaller sieve openings might present a technical challenge. Furthermore, care should be taken as the installation of a more restrictive filtration element could significantly alter the pressure profile inside the extruder and thus the pressing process. Uitterhaegen et al. (2015) have suggested raising the feed rate to obtain a lower filtrate foot content. A higher seeds inlet flow rate would result in a higher filling of the trituration zone inside the extruder, further leading to a decreased crushing capacity and thus larger solid particles. Similarly, a decrease in the screw rotation speed would diminish the mechanical action of the trituration zone, resulting in a lower amount of fine particles that are easily driven through the filter element (Evon et al., 2013). Like for a lowering of the sieve openings of the filter element, it must be taken into account that a change in these extrusion parameters would significantly alter the pressing process.

4.2. Influence of operating parameters

Next to the screw configuration, the influence of the extrusion operating conditions has been the subject of many research studies, in which the extrusion process is often optimized for a specific oilseed species (Dufaure et al., 1999a; Evon et al., 2013; Kartika et al., 2005, 2006; Sriti et al., 2012; Uitterhaegen et al., 2015). As opposed to single-screw extrusion, where the process throughput is dependent on the screw speed and the pressure profile, twin-screw extrusion allows the adjustment of several independent process variables, including the feed flow rate, the screw rotation speed and the temperature profile along the screw axis. This leads to a high process flexibility and optimization potential. Dufaure et al. (1999a) have emphasized the importance of the feed rate on the extrusion process performance. On the one hand, when an insufficient feed flow rate is applied, the extruder, and in particular the space around the reverse screws, does not fill up with material and the dynamic plug, which enables effective oil expression through pressure build up, is unable to form. On the other hand, with an excessive seeds inlet flow rate, the extruder becomes too filled, leading to a blocking of the filtration element by solid particles and further to the backflow of material to the feeder and consequently the clogging of the extruder. This effect could be counteracted through an increase of the screw rotation speed, as this reduces the degree of fill inside the extruder. Based on this, it is clear that the performance of the extrusion-pressing process strongly depends on the degree of fill of the extruder, rather than on the feed rate or the screw speed as a sole parameter. This was illustrated by Uitterhaegen et al. (2015) for the pressing of coriander seeds, where a parameter C_F, the device's filling coefficient (kg/h rpm), was defined as the ratio of the seeds inlet flow rate to the screw rotation speed. It was found that when the feed rate and the screw speed were varied in the same proportion, and thus the device's filling coefficient was maintained stable, this did not lead to a significant change in the pressing efficiency of the extruder. The use of such parameter describing the degree of fill of a twin-screw extruder-press may also be deemed valuable during process scale-up considerations. In terms of energy consumption, it was reported for both coriander oil and sunflower oil pressing that a concurrent increase in the feed rate and screw speed, while maintaining the device's filling coefficient, results in a decreased energy consumption, which may be due to the reduced residence time of the material inside the extruder (Kartika et al., 2006; N'Diaye and Rigal, 2000; Uitterhaegen et al., 2015). Thus, the pressing operation could be executed at a higher productivity with reduced cost. Several authors have reported the presence of a practical working range of parameter variation that allows effective filtration (Dufaure et al., 1999a; Kartika et al., 2005; Prat et al., 1999, 2002). These parameters include the operating conditions directly influencing the degree of fill of the extruder, i.e. the feed rate and the screw speed, as well as restrictions regarding the extrusion temperature and the raw material moisture content. Beyond this working range, either blocking of the extruder or no L/S separation is encountered. For the thermomechanical pressing of sunflower seeds, the reported effective filtration zone in terms of feed rate and screw speed corresponds to a filling coefficient C_F of between 0.05 and 0.20 kg/h rpm, with superior extraction efficiencies for the highest levels of the filling coefficient (Dufaure et al., 1999a). However, it must be noted that this parameter does not take into account the effect of the screw configuration or the pressing temperature, which are both important parameters with a key impact on the degree of fill of the extruder.

The impact of the pressing temperature on the performance of the extrusion pressing process consists of several different aspects. On the one hand, an increase in temperature leads to a decrease in the oil viscosity and to the coagulation of the protein fraction of the seeds, which enhance the oil expression capacity and facilitate its release through the fibrous matrix (Dufaure et al., 1999a). Further, high processing temperatures may approximate the glass transition temperature of the cake material, causing an important increase in the deformability and the mobility of the cellular structure, in turn leading to an enhanced oil extraction (Bouvier and Campanella, 2014). The positive impact of high temperatures on the pressing process was illustrated for the pressing of sunflower seeds, where an oil extraction efficiency of 70% was obtained at a pressing temperature of 120 °C, while this was only 66 or 62% at a temperature of 80 or 100 °C, respectively (Dufaure et al., 1999a). Next to this, the energy consumption of the extruder was also found to decrease from 30 to 26 A with an increasing temperature from 80 to 120 °C, owing to the reduced viscosity of the seed material. It must be noted, however, that high processing temperatures may induce undesirable changes in the oil and press cake quality, such as the destruction of thermosensitive compounds and oil discoloration (Mridula et al., 2015; Vadke and Sosulski, 1988). On the other hand, a strong reduction of the oil viscosity and the press cake consistency associated with high pressing temperatures may exert a negative impact on the pressing capacity of the extruder, as the increased material fluidity may lower the degree of fill and the residence time of the material inside the extruder (Gautam and Choudhury, 1999a). Furthermore, with high temperatures inducing the glass transition of the cake material, the excessive loss in consistency and fiber entanglement of the lignocellulosic matter may further render the pressure build up and oil extraction more difficult (Wiesenborn et al., 2001). This was observed for the pressing of jatropha seeds, where an increase in the pressing temperature from 80 to 120 °C resulted in a reduced oil yield and a higher foot content of the filtrate due to a less efficient L/S separation in the pressing zone showing an insufficient degree of fill (Evon et al., 2013). As the degree of fill of the extruder further depends on other parameters such as the screw configuration, the feed rate and the screw speed, the optimal pressing temperature varies with the aforementioned operating parameters, as well as the raw material. It has been reported for the pressing of sunflower seeds that the oil extraction efficiency is enhanced by low pressing temperatures when applying a low seed feed rate, i.e. at a low degree of fill, while high temperatures are favorable and avoid blocking of the extruder with high feed rates, especially when the screw speed is also low, which further contributes to a high degree of fill (Kartika et al., 2006). Several authors have described an excessive filling of the extruder, in particular near the pressing zone, when using low pressing temperatures (Kartika et al., 2005, 2006; Uitterhaegen et al., 2015). For the pressing of coriander and sunflower seeds, a low pressing temperature of 65–80 °C, in combination with other restrictive extrusion conditions, resulted in an accumulation of solid particles upstream from the pressing zone and thus near the filtration element, leading to high foot contents of the extrusion filtrate and, consequently, reduced oil recoveries (Kartika et al., 2005; Uitterhaegen et al., 2015). Furthermore, as both the high degree of fill and the high material viscosity lead to a high energy consumption of the extruder, the specific mechanical energy of the process became very important for such low temperatures and reached values of up to 1.5 kW·h/kg of produced oil.

A last, yet fundamental parameter showing a great impact on the extrusion-pressing process consists of the raw material characteristics. This comprises the seed moisture content and the type of oilseed, but also the specific variety of the species and potential differences in the seed and oil composition due to variations in the cultivation conditions. In contrast to single-screw extruder-presses, which are typically designed for a single oilseed species, twin-screw extruders show high process flexibility due to their modular design and may be employed for the thermomechanical pressing of different types of oilseeds. This has been illustrated by Amruthraj et al. (2014), who have designed a twin-screw extruder-press which, through the installation of different barrel configurations, could serve as a means for efficient pressing of Pongamia pinnata seeds on the one hand, and as highly flexible R&D equipment for the processing of different oilseeds on the other hand. Even though no studies analyzing the varietal effect or the influence of cultivation conditions on the pressing process have been reported for twin-screw extrusion so far, these parameters have been shown to exert a significant impact on the single-screw pressing process (Savoire et al., 2010; Zheng et al., 2003). As an example, important differences were observed for the single-screw pressing of two varieties of flaxseed and were explained through the presence of a thinner hull for a particular variety, which renders the material more compressible and reduces its porosity for drainage, thus leading to a reduced oil extraction (Zheng et al., 2003). The moisture content of oilseeds is of key importance to the pressing efficiency of the process, as moisture acts as a lubricant and shows a large impact on the rheological properties of the cellular material inside the extruder. Many studies have described this effect for single-screw extrusion, where the general trend consists of an increase in the oil extraction efficiency with a reduction in the seed moisture content. This increase in efficiency is due to an enhanced pressure build up with an increased seed rigidity, as shown for flaxseed (Zheng et al., 2003), rapeseed (Vadke and Sosulski, 1988), crambe seed (Singh et al., 2002) and cuphea seeds (Evangelista and Cermak, 2007). The optimal seed moisture content for efficient thermomechanical pressing is largely dependent on the raw material and the operating conditions of the extrusion process, which are determinant for the degree of fill and include the pressing temperature, the screw profile, the seeds feed rate and the screw speed. While several studies have reported the presence of an optimal moisture content beyond which the extraction efficiency no longer increases or even decreases, other reports have found a continuous increase in oil recovery up to the point, often near a moisture content of 3–4%, where a further decrease in moisture caused blocking of the extruder due to the excessive pressure and friction of the very rigid material (Evangelista and Cermak, 2007; Singh et al., 2002). For example, an optimal moisture content of 7% was observed for the single-screw pressing of rapeseed (Singh and Bargale, 2000) and linseed (Singh and Bargale, 1990), while other researchers reported a maximum pressing efficiency for rapeseed at 5% moisture content (Vadke and Sosulski, 1988) and for jatropha seeds, the optimal moisture was found as high as 10% (Pradhan et al., 2011). Only one study has evaluated the influence of moisture on the performance of a twin-screw extrusion-pressing process. For the extraction of sunflower oil, sunflower seeds were conditioned to different moisture contents between 6 and 2% through oven drying prior to twin-screw pressing (Dufaure et al., 1999a). The authors found that a drying pre-treatment of the seeds led to important increases in the foot content of the filtrate, for example from 10% to 25% for a reduction in seed moisture content from 6% to 4%. Therefore, lower oil yields were obtained with intensively dried seeds due to the significant oil losses during centrifugation of the filtrate showing a high foot content, even though there was a decrease in the residual oil content of the press cake, indicating enhanced pressing capacity. This increased filtrate foot content has also been observed for the single-screw pressing of crambe seeds (Singh et al., 2002) and lesquerella seeds (Evangelista, 2009), with a reported 1% increase per 1% reduction of the moisture content for the latter. The increase in foot content results from an excessive particle size reduction of the material, as very small particles are easily driven through the filter element, due to the enhanced friction and crushing capacity of the extruder with seeds of increased rigidity. For the twin-screw pressing of sunflower seeds, the authors further argued that excessively dried seeds show an increased friability to the detriment of the material elasticity, rendering the formation and compression of the dynamic plug more difficult (Dufaure et al., 1999a). Next to this, a significant increase of the phosphorus content of the oil was observed with dried seeds. For example, the phosphorus content of the pressed oil increased from 85 to 106 mg/kg and further to 123 mg/kg for seeds showing a moisture content of 6, 5 and 2%, respectively. The acid value, however, remained stable below 2 mg KOH/g oil. The increased phosphorous content was explained by an enhanced crushing of seeds containing low moisture, which is also illustrated by the increased foot contents, and which results in an intensified rupture of the cell wall structures and thus an increased co-extraction of the membrane phospholipids. This phenomenon has also been observed for the single-screw pressing of cuphea seeds, where a significant increase in the phospholipid content of the oil was found with a decreasing seed moisture content (Evangelista and Cermak, 2007). Further research is necessary in order to gain a clear overview of the impact of the moisture content of the raw material on the process performance of twin-screw extrusion-pressing and on the quality of the obtained vegetable oil.

A general overview of the reports on the optimization of twin-screw extrusion-pressing processes for various oilseeds is presented in Table 1. A considerable number of studies have focused on the extraction of sunflower vegetable oil, which presents one of the major vegetable oils with an annual world production of 15 million tons in 2015/2016 and a continuously growing demand (United States Department of Agriculture, 2016). Sunflower oil is widely used in the food industry as a cooking oil and as an important component of soft spreads. Therefore, great importance is attached to its quality and the method of extraction. Pressing is most commonly preferred as this results in a vegetable oil of higher quality when compared to *n*-hexane solvent extraction, and does not lead to the presence of solvent traces in the end products. High oil recoveries of 85–94% have been attained through both lab-scale and pilot-scale operations using a twin-screw extruder (Table 1). The use of a counter-rotating twin-screw extruder with dehulled sunflower seeds seems to result in a particularly high process efficiency and productivity, at a relatively low cost (0.11 kW·h/kg oil produced) (Isobe et al., 1992). However, in this case, the cost of the dehulling treatment should be taken into account. Nevertheless, the oil recoveries reached through twin-screw pressing remain comparable to those commonly obtained for single-screw pressing of sunflower seeds, with reported efficiencies of up to 85% for pilot-scale, single-screw cold pressing processes (Jacobsen and Backer, 1986). Less work has been conducted for other oilseeds such as coriander and jatropha and for the former, the attained oil recoveries are limited and always below 50%. Therefore, further research should be carried out in order to enhance these extraction processes on the one hand, and to evaluate the performance of twin-screw pressing processes of other oilseed varieties showing different material characteristics. However, due to the practical limit on the lowest residual oil content that is attainable through mechanical pressing, the extraction efficiency of optimized pressing operations will most often belong to the same range as those obtained through single-screw processes. The advantages of twin-

Table 1
Overview of research reports on the optimization of thermomechanical pressing of oilseeds using twin-screw extrusion.

Seed species (oil content, % db)	Twin-screw extruder type	Feed rate (kg/h)	C_F (kg/h rpm)	Oil recovery (%)	Cake residual oil (% db)	SME (kW·h/kg oil produced)	Remarks	Reference
Sunflower (58.6%)	Partially intermeshing, counter-rotating (Suehiro Iron Works)	50–58	2.95–3.41	93.6	8.3	0.11	Dehulled seeds, high oil content	(Isobe et al., 1992)
Sunflower	Consecutive intermeshing and non-intermeshing zone, co-rotating (Clextral)	70	1.75	85–90	15	not reported	High pressing temperature (120 °C)	(Bouvier and Guyomard, 1996)
Sunflower (50.9%)	Intermeshing, co-rotating (Clextral BC45)	22	0.15	79.0	14.4	0.34	Seeds with reduced moisture content (5.0%)	(Dufaure et al., 1999a)
Sunflower (48.5%)	Intermeshing, co-rotating (Clextral BC45)	18	0.24	85.3	12.4	0.67	Spacing of reverse screw elements. Two filtration sections	(Kartika et al., 2006)
Coriander (21.9%)	Intermeshing, co-rotating (Clextral BC21)	2.3	0.05	45.0	16.6	not reported	High foot contents (at least 48%)	(Sriti et al., 2012)
Coriander (27.7%)	Intermeshing, co-rotating (Clextral BC21)	3.9	0.04	46.9	16.8	0.88	High pressing temperature (120 °C)	(Uitterhaegen et al., 2015)
Jatropha (33.7%)	Intermeshing, co-rotating (Clextral BC21)	5.2	0.03	70.6	7.7	0.31	High foot contents (at least 30%)	(Evon et al., 2013)

screw extrusion-pressing over its single-screw counterpart are mainly based on economic considerations. This may be illustrated for jatropha seeds, where twin-screw extrusion resulted in a lower oil recovery (71%) as compared to single-screw extrusion (89%), but showed a considerably lower specific mechanical energy in terms of energy consumption per unit of pressed oil (0.3 kW·h/kg oil against 1.6 kW·h/kg oil) at comparable operating scales (Evon et al., 2013; Karaj and Müller, 2011). Therefore, even though the twin-screw process was less efficient in terms of oil extraction, the oil was much cheaper to produce, resulting in an extraction process with enhanced economic feasibility. In addition, several authors have reported superior oil and press cake quality in terms of organoleptic properties and minor compounds obtained through twin-screw extrusion, as compared to single-screw extrusion, which mainly results from the excessive exposure to high temperatures in the case of single-screw extrusion due to material pre-treatments, high friction and poor mixing. (Dufaure et al., 1999a; Isobe et al., 1992; Li et al., 2014; Singh and Bargale, 2000).

5. Solvent-assisted vegetable oil extraction

The existence of a practical limit on the maximal attainable oil recovery has limited the use of thermomechanical pressing as a sole method for vegetable oil extraction in the oilseed processing industry. Seeds are most commonly pre-pressed to extract a significant fraction of the vegetable oil at a low cost, and subsequently solvent extracted to obtain a high oil recovery of typically more than 95% and a press cake with a very low residual oil content. Commonly applied contact-equilibrium extraction processes are typically very solvent and energy consuming, as well as requiring large processing volumes and long processing times. Here, the implementation of a twin-screw extruder as an extractor with subsequent L/S separation could be an interesting approach. A limited number of studies have been conducted on the development of an aqueous extraction process using a co-rotating twin-screw extruder for the recovery of sunflower oil (Evon et al., 2007, 2009, 2010a, 2010b). For this, different processing sections can be distinguished inside the twin-screw extruder barrel. After introduction at the feed inlet, the raw material passes a first trituration zone consisting of monolobe and/or bilobe paddles that ensure profound crushing and size reduction of the particles. Then, deionized water is injected in a liquid state and at ambient temperature into the extruder barrel by the use of a piston pump, while an additional set of bilobe paddles further downstream provides intimate mixing of both phases. Vegetable oil is extracted from the seeds in the form of an oil-in-water emulsion stabilized by phospholipids and proteins that are co-extracted during the aqueous process and present natural surface active agents. Finally, the presence of reverse screws near the end of the extruder and immediately after the filtration module allows pressure build up of the material and consequently, effective filtration of the mixture. A significant improvement of the oil recovery was reported, from 41 to 55%, when applying twin-screw extrusion rather than a small-scale batch extraction of sunflower oil with water as the extracting solvent (Evon et al., 2007). This improvement was attributed to the superior crushing action of the twin-screw extruder, leading to efficient cell lysis. On the other hand, a significant amount of intact cell structures were observed in the cake resulting from the batch aqueous extraction process, resulting in a low oil extraction capacity. Next to a 35% increase in oil recovery, the twin-screw extrusion process also brought about a 50% reduction of water usage, a greatly shortened extraction time, and the avoidance of a seed crushing pre-treatment. These results illustrate the potential of twin-screw extrusion as a means for process intensification. Furthermore, the resulting oil-in-water emulsion showed a significantly larger oil droplet size with twin-screw extrusion as compared to a batch extraction. Nevertheless, the emulsion showed satisfactory stability over time and a recent market study revealed its potential as a co-emulsifier in the cosmetics industry (Evon et al., 2016). As such, additional de-emulsification steps in order to isolate the vegetable oil fraction are avoided, which adds to the economic feasibility of the process. During the aqueous extraction of oil from sunflower seeds in a twin-screw extruder, important difficulties were encountered near the filtration zone. In order to obtain an effective L/S separation, additional lignocellulosic material had to be added before the pressing zone, which aided in the pressure buildup and the formation of a dynamic plug near the reverse screw elements. However, even with the addition of wheat straw at 7% of the seed flow rate or when introducing the whole sunflower plant, which shows a high amount of lignocellulosic material, the process was marked by an unsatisfactory L/S separation (Evon et al., 2010a, 2007, 2010b). As a result, the attained oil recoveries remained relatively low at 55%, which is lower than the oil recovery of 85% that can be reached through direct pressing of the sunflower seeds in the same twin-screw extruder (Evon et al., 2007; Kartika et al., 2006).

The disadvantage of water as a solvent for vegetable oil extraction is that the obtained filtrate consists of three distinct phases, i.e. an insoluble phase (the filtrate foot), a hydrophilic phase containing mainly extracted water-soluble compounds such as proteins and hemicelluloses, and a hydrophobic phase consisting of an oil-in-water emulsion stabilized by proteins and phospholipids that often requires further de-emulsification process steps after its separation. Therefore, alternative environmentally friendly and non-toxic solvents, such as alcohols, have gained considerable interest as extracting solvents for vegetable oils (Navarro et al., 2016). A solvent-assisted twin-screw extrusion process using alcohols acidified with phosphoric acid for the extraction of vegetable oil has been developed and evaluated by Gaset et al. (1999). The addition of an acid enhances the oil extraction capacity, as it has been shown to disintegrate the cell membranes of the oil bodies, which, in conjunction with the mechanical action of the extruder, facilitates oil liberation (Dufaure et al., 1999b; Gaset et al., 1999). Next to this, phosphoric acid acts as a degumming agent and associates with the phospholipids naturally present in the vegetable oil, forming a hydrophilic complex that remains in the press cake after oil extraction. Therefore, this twin-screw process integrates an oil extraction operation with a simultaneous degumming operation and may lead to important reductions in subsequent oil refining steps. This process was successfully applied for the vegetable oil extraction from sunflower seeds using 2-ethylhexanol with added phosphoric acid (Dufaure et al., 1999b). Significant improvements in the oil extraction, as well as the oil quality in terms of phosphorus content, were obtained upon the injection of acidified 2-ethylhexanol when compared to a solvent-free pressing process under the same conditions. An oil recovery of 90% was attained with a relatively low L/S ratio of 1.30 and a phosphoric acid addition of 0.24 (mass ratio of H_3PO_4 to seeds). Further, the authors reported that the addition of phosphoric acid aids in the L/S separation near the filtration module and an increased acid addition allows the application of a higher L/S ratio while maintaining a satisfactory filtration. High quality vegetable oils with an organic phosphorous content below 30 ppm were obtained, while thermomechanical pressing under the same conditions but without the injection of solvent or acid resulted in oil with a phosphorous content of 235 ppm (Dufaure et al., 1999b). Another solvent class that has recently been of interest for the green solvent extraction of vegetable oils is presented by fatty acid methyl esters (FAMEs). These bio-derived solvents are prepared from vegetable oils and are non-toxic, renewable and biodegradable, while showing technical performances comparable to those of common petrochemical solvents (Chemat et al., 2012). Furthermore, the resulting miscella mixtures of oil in FAMEs could find direct utilization as bio-fuels. Kartika (2008) evaluated the use of linoleic methyl esters for the extraction of sunflower oil in a co-rotating twin-screw extruder. A good process performance was obtained, as the methyl esters showed high oil extraction capacity and the application of a relatively low L/S ratio of 0.65 led to a high oil recovery of 91% and further to a good L/S separation near the filtration module with, consequently, a low filtrate foot content (4%).

As it has been demonstrated for sunflower seeds that high oil recoveries of up to 85% can be reached through twin-screw extrusion-pressing without any solvent injection (Kartika et al., 2006), the combination of both a pressing step and a green solvent extraction of the press cake could be an interesting approach to attain very high oil recoveries in a sustainable manner. A novel oil extraction process as such, including a first pressing step using an extruder configuration based on the one optimized by Kartika et al. (2005, 2006) for the pressing of sunflower seeds, and a subsequent second passage of the press cake involving the green solvent extraction of its residual oil, was considered by several researchers for sunflower oil recovery (Evon et al., 2009; Kartika et al., 2003). Evon et al. (2009) assessed a second extruder passage aiming at the aqueous extraction of the cake residual oil, using the same twin-screw extruder, but with a configuration based on the one previously used for the aqueous extraction of whole sunflower seeds (Evon et al., 2007). The total oil recovery for this process reached 74%, though the contribution of the aqueous extraction stage was never higher than 1%. Similarly as for the aqueous extraction of whole sunflower seeds, the low extraction capacity was mainly the result of an inefficient L/S separation near the filtration module, resulting in high foot contents of at least 30%. A better process performance was obtained when using FAMEs as the extracting solvent, resulting in a total extraction efficiency of 96% based on the residual oil content of the meal (Kartika et al., 2003). A highly innovative oil extraction process was developed through the combination of both extrusion steps in a single twin-screw extruder passage (Evon et al., 2009; Kartika et al., 2010). This involves an extruder configuration with two separate filtration modules in order to obtain a first filtrate consisting of free oil from the pressing stage and a second filtrate further downstream resulting from the green solvent extraction stage (Fig. 1). The solvent is injected into the extruder barrel after the first filtration and pressing zone. When implementing an aqueous extraction, the efficiency was found to be restricted by important extruder limitations, leading to a modest oil recovery of 78% and a high meal residual oil content of about 10% (Evon et al., 2009). These limitations include a restriction to the water injection rate in order to avoid a backflow effect and a restriction to the fiber addition to avoid clogging of the extruder. These restrictions are further strengthened by the relatively high filling of the extruder (0.22 kg/h rpm), which is necessary in order to obtain an effective crushing and primary pressing process. As a result, the L/S ratio that could be applied was always lower than 2, limiting the aqueous extraction capacity. Further, the L/S separation remained unsatisfactory, even with a maximal fiber addition of 13% of the seeds feed rate. Next to this, the authors argue that even though the complete denaturation of the protein fraction during extrusion leads to a reduced stability of the obtained oil-in-water emulsion, it also renders the emulsification process more difficult and thus decreases the efficiency of the aqueous extraction (Evon et al., 2009). Some of the aforementioned limitations were overcome by the use of FAMEs as the extracting solvent, rather than water (Kartika et al., 2010). As FAMEs show a superior oil extraction capacity, lower L/S ratios can be applied and a good L/S separation is obtained near the second filtration zone without the necessity of adding lignocellulosic material. The researchers implemented several compression and relaxation sequences in the screw profile, which aided the diffusion of the solvent in the vegetable matrix, as well as the diffusion of the vegetable oil in the extracting solvent. Furthermore, this configuration prevented the backflow of material in the extruder barrel, leading to a first filtrate of high quality virgin vegetable oil. The combined extraction process resulted in a total sunflower oil recovery of 85% and a meal with only 2.5% residual oil, leading to a meal-based extraction efficiency of 98%. Furthermore, the oil showed good quality with acid values below 0.7 mg KOH/g oil. Such combined processes show great industrial potential owing to their compactness and flexibility, high oil recovery and the absence of an interdependence between conventionally applied seed preparation steps, a pre-pressing operation and a solvent extraction of the press cake. They may thus result in important reductions in capital and operational expenditures and may represent a significant means for process intensification. However, these multistage processes are still in an early development stage and further research is necessary to enhance their overall performance, validate their effectiveness for different plant species and assess their industrial feasibility. Next to this, the evaluation of other green extracting solvents, e.g. (bio-)ethanol or supercritical CO_2, and novel extruder configurations to enhance oil extraction, such as the injection of the extracting solvent in a countercurrent manner, will present important research challenges for years to come.

6. Press cake applications

With a view to the valorization of extrusion by-products, the press cake could find applications in several different industries. Firstly, the cake material could be subjected to combustion, gasification or pyrolysis, rendering it a valuable source of energy that could potentially be used to render the process energy self-sufficient (Gerçel, 2002). Further, it could serve as a high value animal feed owing to its greater protein solubility as compared to a single-screw press cake (Dufaure et al., 1999a; Isobe et al., 1992; Li et al., 2014). Next to this, the material, which is mainly composed of proteins and lignocellulosic fibers, may be considered as a natural composite. It could then find valuable applications in the materials industry through its transformation into renewable and biodegradable materials that could serve as sustainable alternatives to commercial materials such as wood products or particleboards, which often use toxic resins and can lead to harmful VOC emissions (Uitterhaegen et al., 2017). Self-bonded materials with good mechanical and/or thermal insulation properties have been manufactured through thermopressing for sunflower (Evon et al., 2014b, 2012, 2015a), jatropha (Evon et al., 2014a) and coriander (Uitterhaegen et al., 2017) twin-screw cakes, through compression molding for a whole sunflower plant cake (Evon et al., 2015b), and through injection-molding for a sunflower twin-screw cake (Rouilly et al., 2006). Furthermore, Uitterhaegen et al. (2017) have shown that a press cake resulting from twin-screw extrusion leads to materials with a considerably enhanced mechanical strength and water resistance, as compared to materials produced from a single-screw cake.

7. Conclusions

Twin-screw extrusion technology exhibits promising perspectives in the field of vegetable oil extraction, especially when integrating several extraction stages in a single extruder passage. However, extensive additional research is crucial in order to further develop these processes and assess their industrial feasibility. The twin-screw press cake has been shown to be particularly valuable for the feed industry or for the manufacturing of renewable materials. Therefore, twin-screw extrusion could present an important asset for process intensification and the development of oil crop biorefineries, which will become of increasing importance for years to come in view of the recent critical pressure towards sustainable processing.

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