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Review article

Planetary roller extruders in the sustainable development of polymer blends and composites – Past, present and future

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Abstract. Screw extruders as continuous flow reactors allow the synthesis of new polymers, preparation of polymer blends and composites, and modification or functionalization of commercially available polymers. Literature data shows that the twin screw extrusion is the most popular solution used for this purpose. In contrast, the number of scientific papers on alternative methods, such as multi-screw extruders, is somewhat limited. This paper is the first review of the application of planetary roller extruders in the compounding and reactive processing of polymer blends and composites. To fill current knowledge gaps, we discuss the advantages and disadvantages of planetary roller extruders compared to other screw extruders. Moreover, we summarize recent advances in planetary roller extrusion in producing thermal sensitive and biodegradable polymeric materials, rubber compounds, materials for 3D printing, or plastics and rubber recycling. This work also proposes the possible scenarios for further sustainable development of polymer blends and composites using planetary roller extruders.

Keywords: *planetary roller extruders, polymer blends and composites, recycling, reactive extrusion, green and sustainable chemistry*

1. Introduction

Polymer blends and composites are commonly used in a wide range of industrial applications, *e.g.,* automotive industry [1], biomaterials [2], food packaging [3], additive manufacturing [4], construction and building materials [5], *etc.*

Increasing demand for polymer-based materials is related to their relatively low cost and specific properties, such as good mechanical properties, low density, corrosion resistance, thermal stability, chemical resistance, *etc.* Moreover, polymer blends and composites can be manufactured by various processing methods [6], enabling the customization of the performance properties of the resulting materials and the increase of energy efficiency in processing. Therefore, it is fully justified to search for new and cost-effective polymer processing methods or optimization of already existing solutions.

Nowadays, extrusion is one of the most important technologies in the polymer processing industry [7–9]. According to the ASTM D 883 standard ('*Standard Terminology Relating to Plastics*') the term '*extrusion*' is defined as: '*a process in which heated or unheated plastic is forced through a shaping orifice (a die) in one continuously formed shape, as in film, sheet, rod, or tubing*'. The definition of extrusion in ISO 472 standard ('*Plastics – Vocabulary*') is very similar to ASTM D 883 standard, and the term '*extrusion*' is specified: '*as a process whereby heated or unheated plastic forced through a shaping orifice becomes one continuously formed piece*'. Considering these definitions, 'conventional' extrusion is a

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solvent-free method used for melting, homogenization, pumping and shaping of polymeric materials. Suitable selection of commercially available components and/or the optimization of extrusion conditions allows for the preparation of polymer blends and composites with tailored and well-defined properties [10–12]. This approach can also be applied to the modification and/or functionalization of fillers [13–15] and plasticizers [16, 17], commonly used in polymer technology.

Therefore, extrusion technologies should be considered an interesting and environmentally-friendly alternative for more complicated methods dedicated to preparing new materials, such as periodic, multi-step, and time-consuming procedures, which generally require additional purification of products [18, 19].

The main advantages of extrusion are continuity and short process time, high mixing efficiency, high capacity, and good quality-to-cost ratio for obtained products. Moreover, due to the application of mixing devices commonly used in the industry, the suitable modeling and optimization strategies cause potential risks related to the transfer of results from laboratory to industrial scale are limited [20, 21].

The mentioned advantages, in combination with the diversity and versatility of extrusion technologies, result in their growing popularity for application in such strategic sectors as the food industry [22–24], pharmaceutical industry [25–27], or polymer engineering [28–30].

Moreover, current research trends in this field have shown that more and more attention is focused on the sustainable development of extrusion of pharmaceutics [31], food [32], polymer blends, and composites [33–35] dedicated to 3D and 4D printing technologies. Recent advances in this field were comprehensively summarized and discussed by Ameta *et al*. [36].

However, it should be pointed out that for more complex multi-phase polymeric materials and/or specific extrusion conditions (*e.g.*, reactive extrusion, solid state shear extrusion, *etc.*), application of commonly used single screw and twin screw extruders may not be adequate to achieve the desired material quality and process efficiency.

This work aims to present the state-of-the-art regarding the application of planetary roller extruders in green and sustainable polymeric materials and technologies, which includes a discussion about the advantages and limitations of this technology. Moreover, the possible scenarios for applications of planetary roller extruders in the further development of polymer blends and composites were also highlighted.

2. Physical blending *vs.* reactive extrusion in polymer technology

Physical blending, defined as simple mixing in the melt state without any chemical reactions between components, usually results in weak interfacial adhesion between phases and incompatibility of obtained polymeric materials [37–39] and as a consequence, their unsatisfactory performance properties.

One of the most efficient methods for improving the interfacial interactions and compatibility of polymer-based systems or their recycling products is reactive extrusion [40–42]. In this approach, designed chemical reactions are carried out '*in situ*' between the components used to modify or functionalize the chemical structure of existing polymers or to produce new polymeric materials in a highly efficient and flexible way. Reactive extrusion has recently been considered a promising and green solution for mechano-chemistry and organic synthesis [43–45], because the chemical reactions can be performed in solvent-free or solvent-minimized systems [46].

In 2019, the International Union of Pure and Applied Chemistry (IUPAC) identified the top ten emerging technologies in chemistry with the potential to make our planet more sustainable. According to the proposed ranking, reactive extrusion, along with flow chemistry, are considered the most important chemical innovations that could change our world [47]. Therefore, the search for new strategies in reactive extrusion and further development of novel polymeric materials based on the principles of green and sustainable chemistry and engineering is gaining more and more attention [48–50].

In this field of research, interdisciplinary studies focused on finding and understanding the relationship between extruder construction (*e.g.*, extruder type, screw design, die construction, *etc.*) (mechanical engineering), extrusion conditions optimization (chemical engineering), desired chemical reactions mechanism or efficiency (chemical science) and final performance properties of the obtained polymer blends and composites (materials science), seems to be the most promising approach.

3. Extruders as chemical reactors

Reactive extrusion of polymers is not a new concept; the first attempts in this field were made in the early 1920s by using screw machines for rubber polymerization [51]. However, this technology still has a great undiscovered potential for the development of novel polymeric materials with unique properties (*e.g.*, biodegradability [52], electrical conductivity [53], antibacterial [54], self-healing properties [55], *etc.*), or in plastics and rubbers recycling [56, 57] and upcycling [58].

However, further progress in reactive extrusion-based technologies is unfeasible without the development of screw extruders or extrusion-dedicated peripherals. During reactive extrusion, an extruder is used as a horizontal chemical reactor equipped with one, two, three, or more internal screws for the constant conveying of reactants in various forms, including solids, liquids, or gases. This strategy is gaining more and more attention in green and industrially scalable synthesis of different organic compounds [59] as an interesting alternative for ball milling and other periodical methods.

Extruders can be classified into three main groups: single screw extruders (*e.g.*, with smooth barrel/groove or pin barrel), twin screw extruders (*e.g.*, conical/parallel, corotating/counter-rotating, intermeshing/non-intermeshing), and multi screw extruders. However, it should be pointed out that the application of planetary roller extruders in polymer engineering has the longest history among commercially available and industrial-scale applicable multi-screw extruders. Therefore, in this work, only the planetary roller extruders are compared with commonly used in the industry single screw and twin screw extruders.

For comparison, the number of hits related to the terms: 'single screw extruder', 'twin screw extruder', and 'planetary roller extruder' were collected from such databases as Google (www.google.com), GoogleScholar (https://scholar.google.com), Patentscope (https://patentscope.wipo.int), Espacenet (https://worldwide.espacenet.com), Scopus (https://www.scopus.com), Web of Science (https://apps.webofknowledge.com). Searching was performed on 28 June 2023, and the results obtained are summarized in Table 1. As can be observed, regardless of the used database, 'twin screw extruder' is the most popular solution with % of hits in the range of: 67.2–79.1% among considered screw machines. For comparison, % of hits related to the 'planetary roller extruder' was only 0.1–0.4%.

At present, intermeshing a corotating parallel twin-screw extruder is the most common choice for reactive extrusion [28, 51]. This is related to their very good distributive/dispersive mixing combined with a high number of twin screw manufacturers and solutions available on the market. However, for more complex reactions, thermal-sensitive polymers (or additives) and/or specific extrusion conditions, planetary roller extruders seem to be a more suitable solution. In the planetary roller extruder barrel, the central screw and spindles (satellites) are interlocked due to a 45° toothing, which improves contact area with processed material, for a better understanding of the differences in the mixing effectiveness between single-screw extruders, twin-screw extruders, and planetary roller extruders.

Figure 1 presents the number of contact surfaces and mixing points in these devices. As can be noticed, due to a high number of surface contact points, planetary roller extruder is characterized by more efficient mixing of temperature sensitive polymers and in rubber and adhesive compounding compared to other processing methods [60].

Simple calculation indicated that for a planetary roller extruder with diameter: 165 mm (10 spindles (satellites)), length: 1000 mm, a gear tooth module of m = 3.0 and working at screws speed: 50 min^{-1}

Table 1. The number of hits for the terms: 'single screw extruder', 'twin screw extruder' and 'planetary roller extruder' were determined for different databases.

Database		Number of hits		
		'Single screw extruder'	'Twin screw extruder'	'Planetary roller extruder'
Google	(% of hits)	499 000 (32.5%)	1 030 000 (67.2%)	4 480 (0.3%)
GoogleScholar	(% of hits)	24 300 (24.8%)	73 400 (75.1%)	95 (0.1%)
Patentscope	(% of hits)	52 483 (32.2%)	110 063 (67.4%)	692 (0.4%)
Espacenet	(% of hits)	81 155 (27.5%)	213 257 (72.3%)	409 (0.1%)
Scopus	(% of hits)	5 108 (24.3%)	15 867 (75.5%)	37 (0.2%)
Web of Science	(% of hits)	1 686 (20.8%)	6 397 (79.1%)	6 (0.1%)

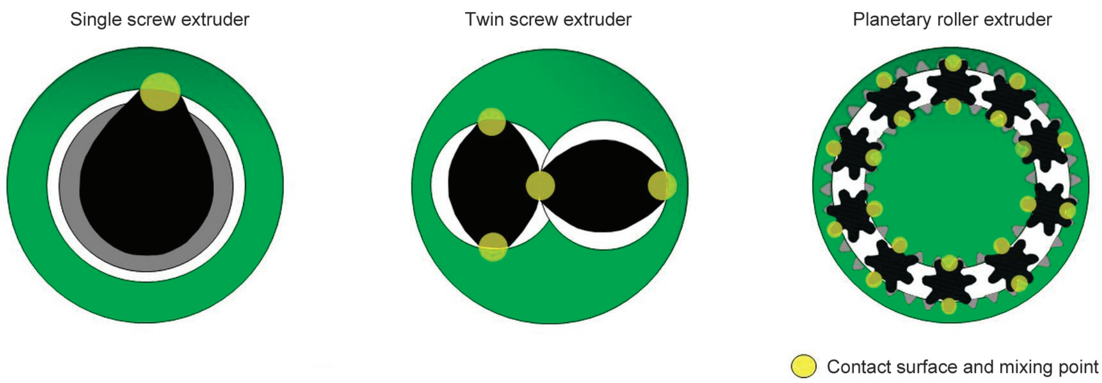


Figure 1. The number of contact surfaces and mixing points in single-screw, twin-screw, and planetary roller extruder (adopted from Takimsan Disli Kesici Ltd. Sti., İstanbul, Türkiye, https://www.takimsan.com).

has approx. 352 m^2/min contact surface. To obtain a similar surface area for a twin screw extruder with a diameter 140 mm, its length should be 40 000 mm, while for a single screw extruder with a diameter 165 mm, the length should be 140 000 mm. This gives planetary roller extruders a significant advantage over single and twin screw extruders with much more limited available barrel surface areas [60].

The mixing mechanism in planetary roller extruders is based on the rolling or calendering-like action, which forces processed material between planetary spindles, central shaft, and outer cylinder [60–62]. The clearance between the planetary spindles (satellites) and the mating surfaces is about 1/4 mm [61, 62]. This allows thin layers of compounded material to be exposed to large surface areas, which results in effective devolatilization, heat exchange (good temperature control), and efficient mixing.

Table 2 presents the comparison of the features between a single screw extruder, twin screw extruder, and planetary roller extruder proposed by Utracki and Shi [61].

Compared to single-screw extruders, twin-screw extruders, and planetary roller extruders have usually a modular screw and barrel construction [19, 40]. This results in their higher flexibility and possibility for easier adaptation for extrusion of materials with complex compositions or different viscosities (*e.g.*, by modification of screw configuration, using of additional feeding or degassing zones, *etc.*). Planetary roller extruders are characterized by excellent distributive mixing, self-wiping, and degassing, which are superior to other screw extruders. For planetary roller extruders, residence time distribution and dispersive mixing are good and acceptable.

Limitations related to feeding materials into the planetary roller extruder are the same as those for single screw extruders due to the similarity in the hooper construction. Figure 2 presents the scheme of feeding section (single screw extruder) and planetary groups in the planetary roller extruder.

Moreover, planetary roller extruders are rather not recommended for high-speed extrusion, and for this purpose, a much better solution is the application of

Table 2. A comparison between the features of single screw extruder, twin screw extruder, and planetary roller extruder (adopted from [61]).

Item		Single screw extruder	Twin screw extruder*	Planetary roller extruder
Screw and barrel design		Non-modular	Modular	Modular
High screw speed		Good	Excellent	Poor
Pressure generation capability		Good	Acceptable	Poor
Residence time distribution		Poor	Good	Good
Feeding	powder	Acceptable	Good	Acceptable
	filler	Poor	Good	Poor
	sticky	Poor	Acceptable	Poor
Distributive mixing		Poor	Good	Excellent
Dispersive mixing		Poor	Acceptable	Acceptable
Wiping		Poor	Good	Excellent
Degassing		Fair	Good	Excellent

*for an intermeshing corotating twin screw extruder

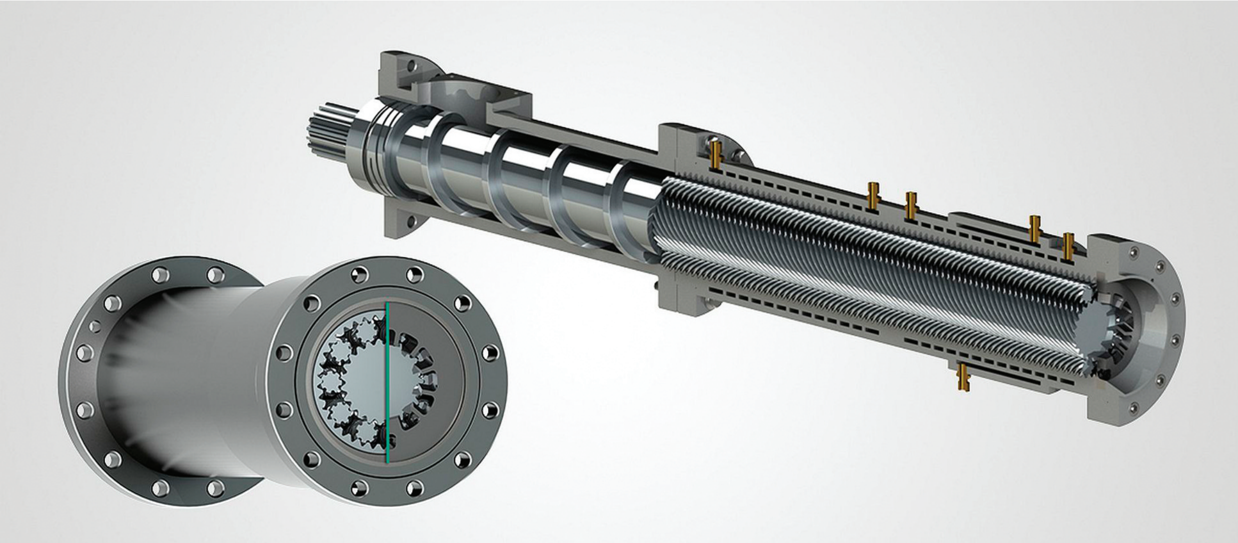


Figure 2. Feeding section and planetary groups in the planetary roller extruder (reprinted with permission from Takimsan Disli Kesici Ltd. Sti., İstanbul, Türkiye, https://www.takimsan.com).

corotating twin screw extruders [51]. The planetary roller extruders have a large contact surface (please see Figure 1), therefore working at high screw speed rotations in this multi-screw system can accelerate the wear of the plasticizing unit (central screw, satellites, and barrel) and, as a consequence, increase the production costs due to the necessity of more frequent of planetary roller extruder maintenance.

The capability for pressure generation by planetary roller extruders is also rather limited. As a result, the planetary roller extruders are usually combined in the cascade with a single screw extruder – a two-step process, which is the common solution in polyvinyl chloride processing. Figure 3 presents the cascade of a planetary roller extruder with a single screw extruder, which includes: 1 – volumetric/gravimetric feeder, 2 – planetary roller extruder, 3 – vacuum-degassing chamber, 4 – single screw extruder, 5 – granulation system, 6 – control panel, and 7 – sieve unit. An alternative solution to the two-step process (planetary roller extruder in cascade with single screw extruder) is the application of gear pumps, which can enhance the pressure on the planetary roller extruder die. However, connecting the gear pump directly with the planetary roller extruder can reduce its regular throughput (the drive motor should have more power), which should be considered before choosing this option.

The advantages and disadvantages of planetary roller extruders are presented in Table 3. As can be observed, the main disadvantage of planetary roller extruders comparing to single or twin screw extruders is their higher purchase price and also higher maintain cost related to plasticizing unit (central screw, satellites and barrel) regeneration or modernization. These costs can be justified considering many advantages related to using of planetary roller extruders, such as modular construction, excellent distributive mixing and reduced energy consumption, *etc.* At present, poor popularity of the planetary roller extruders is mainly related to the limited number of research and development centers with access to the laboratory scale devices (relatively new solution on the market) and as a consequence limited number of scientific papers on the application of this technology.

4. Planetary roller extruders in polymer engineering – past, present, and future

The production history for planetary roller extruders is summarized in the Table 4. The first planetary roller extruders were introduced in Europe in 1960 by Eickhoff-Kleinewerfers Kunststofftechnik (Germany). In 1980, Eickhoff-Kleinewerfers Kunststofftechnik was taken over by Battenfeld GmbH (currently Battenfeld-Cincinnati Germany GmbH) [62]. In 1981, Takimsan Disli Kesici Ltd. Sti. (Türkiye) started production of gears and cutting tools for the gears and in 1986 ran manufacturing of planetary roller extruder parts like planetary barrels and screws; in 2007 started manufacturing complete planetary roller extruder.

In 1986, the company Entex Rust & Mitschke GmbH (Germany) began intensive development of planetary roller extruder-based technologies. After the patent held by Eickhoff-Kleinewerfers Kunststofftechnik expired in 1989, Hermann Berstorff Maschinenbau

Figure 3. Planetary roller extruder in cascade with single screw extruder, where: 1 – volumetric/gravimetric feeder, 2 – planetary roller extruder, 3 – vacuum-degassing chamber, 4 – single screw extruder, 5 – granulation system, 6 – control panel, and 7 – sieve unit (adopted with permission from Takimsan Disli Kesici Ltd. Sti., İstanbul, Türkiye, https://www.takimsan.com).

GmbH (Germany) introduced its own version of the planetary roller extruder [62]. The first manufacturer of planetary extruders in China, Beijing Huateng Zhengcheng Industry and Trade Co. Ltd., was established in 1990. Ltd. continued the development of this technology. In 2010, Yean Horng Machinery C. Taiwan began producing planetary roller extruders. Moreover, in 1998 Extricom Blach Extruder & Components (Germany) invented RingExtruder®, while in 2007, Gneuss Kunststofftechnik GmbH introduced the multi-rotation-system (MRS) extruder. Both of these solutions cannot be classified as 'regular' planetary roller extruders. However, due to their similarity with the planetary roller screw configuration, the development of these devices was also included in the history of planetary roller extruders

Table 3. Advantages and disadvantages of planetary roller extruders.

Advantages	Disadvantages
Compact and modular construction (high flexibility)	Higher costs of purchase and maintenance of plasticizing unit (central screw, satellites and barrel) compared to single or twin screw extruder
Much higher surface area (up to ten times) compared to other compounding systems.	A limited number of used machinery on the market (this is also an advantage because it indicates that already produced machines are still used)
Excellent distributive mixing	A limited number of research and development units with access to this technology
Precise temperature control and efficient cooling	A limited number of scientific reports related to this technology
High range of production capacity (working with the not wholly filled machine also gives good results)	
Excellent self-wiping (short time to change extruded material, minimal waste, efficient degassing)	
Rapid reproducibility and easier upscaling from laboratory scale	
Allows reduction of production costs related to energy consumption, space, and operators	

Table 4. History of planetary roller extruders production.

Producer name	Country	Established
Eickhoff-Kleinewerfers Kunststofftechnik, Bochum	Germany	1960
Battenfeld GmbH (currently Battenfeld-Cincinnati Germany GmbH)	Germany	1943 (planetary from 1980 takeover Eickhoff-Kleinewerfers Kunststofftechnik, Bochum)
Takimsan Disli Kesici Ltd. Sti.	Turkey	1981 (production of complete planetary roller extruders since 2007)
Entex Rust & Mitschke GmbH	Germany	1986
Extricom Blach Extruder & Components		
(from 2017 part of CPM Holdings Inc.)	Germany	1977 (in 1998 RingExtruder®)
Hermann Berstorff Maschinenbau GmbH (currently KraussMaffei Berstorff)	Germany	1892 (In 1989, patent US4889430 for planetary gear extruder)
Beijing Huateng Zhengcheng Industry and Trade Co. Ltd. (B-TRUST)	China	1990
Gneuss Kunststofftechnik GmbH	Germany	1983 (in 2007 MRS extruder)
Yean Horng Machinery C. Ltd.	Taiwan	2010

production. The RingExtruder® is based on twelve screw shafts and a static center shaft (in a planetary roller extruder, this part is rotating). The screws are arranged symmetrically in a ring and rotate in the same direction on their individual axes. According to the producer, this solution compensates the forces known in planetary roller extruders, which partially reduces the limits of barrel and screw wear.

On the other hand, the Multi-Rotation-System (MRS) is a modified version of the single screw extruder. It has a multiple-screw section and delivers polymer melt into a large single-screw drum. This solution contains eight small extruder barrels parallel to the main screw axis. Each small extruder barrel has a 'satellite' screw driven by a ring gear in the main barrel. The satellite screws rotate in the opposite direction of the main screw as they revolve around the screw axis. According to the producer, this system offers significantly better surface area and surface area exchange rates for devolatilization than other available extrusion systems.

Due to the opposite rotation direction and high speed of the satellite screws, the specific surface area for the MRS extruder is around 100 times higher than for a single screw extruder and around 40 times higher compared to a twin screw extruder. However, it was impossible to find any published data comparing the mixing effectiveness of the MRS extruder or RingExtruder® with the planetary roller extruder.

It should be highlighted that the number of planetary roller extruders producers is very limited compared to the manufacturers of single-screw or twin-screw extruders. Table 5 presents an example of planetary roller extruder specifications provided by different producers. As can be observed, a wide range of planetary roller extruder sizes is available

Table 5. Example of planetary roller extruder specifications.

Manufacturer	Size [mm]	Throughput* [kg/h]
Battenfeld-Cincinnati Germany GmbH	140–355	450–5000
Beijing Huateng Zhengcheng Industry and Trade Co. Ltd.	150–550	500–5500
Entex Rust & Mitschke GmbH	30–400	0.3–7000**
Takimsan Disli Kesici Ltd. Sti.	80–215	0.5–2000

*depending on the process,
**can be higher by using a 'heavy-duty' series

on the market, ranging from 30 to 550 mm, with throughputs from 0.3 to 7000 kg/h.

The planetary roller extruder has the potential to replace traditional kneaders, single screws, and twin screw extruders. It is estimated that this approach could result in savings in energy consumption by more than 50% [62]. Polymer processing is an energy-intensive industrial sector [63, 64]. Therefore, energy saving is extremely important, especially considering the current unstable situation related to unexpected Russian aggression on the Ukraine, which already had a significant impact on the global market in 2022 and further consequences of this conflict on a different branch of industry are unknown. Moreover, for planetary roller extruders, costs related to operators' employment and company space can be reduced since all operations are carried out within a single machine.

Historically, the first planetary roller extruders were designed mainly for compounding rigid and plasticized polyvinyl chloride, which was related to the excellent controlling of temperature during extrusion and, consequently, limited degradation of the material during thermo-mechanical treatment. Figure 4 illustrates how the temperature of the barrel and central screw spindle are controlled in the planetary roller extruders.

This solution improves the heat transfer efficiency, resulting in the extruded product with temperature near to temperature control, usually, for industrial-scale planetary screw extruders, a temperature control system based on water or thermal oil as the heating medium, which works at temperatures up to 220 °C (for water) and even up to 430 °C for thermal oil.

However, for small laboratory planetary extruders, conventional electrical heaters could be an interesting solution related to two factors. Firstly, in lab-size machines, the volume of extruded material inside the barrel and throughput is much lower compared to semi-industrial or industrial machines. Therefore, it is easier to control the temperature of processed

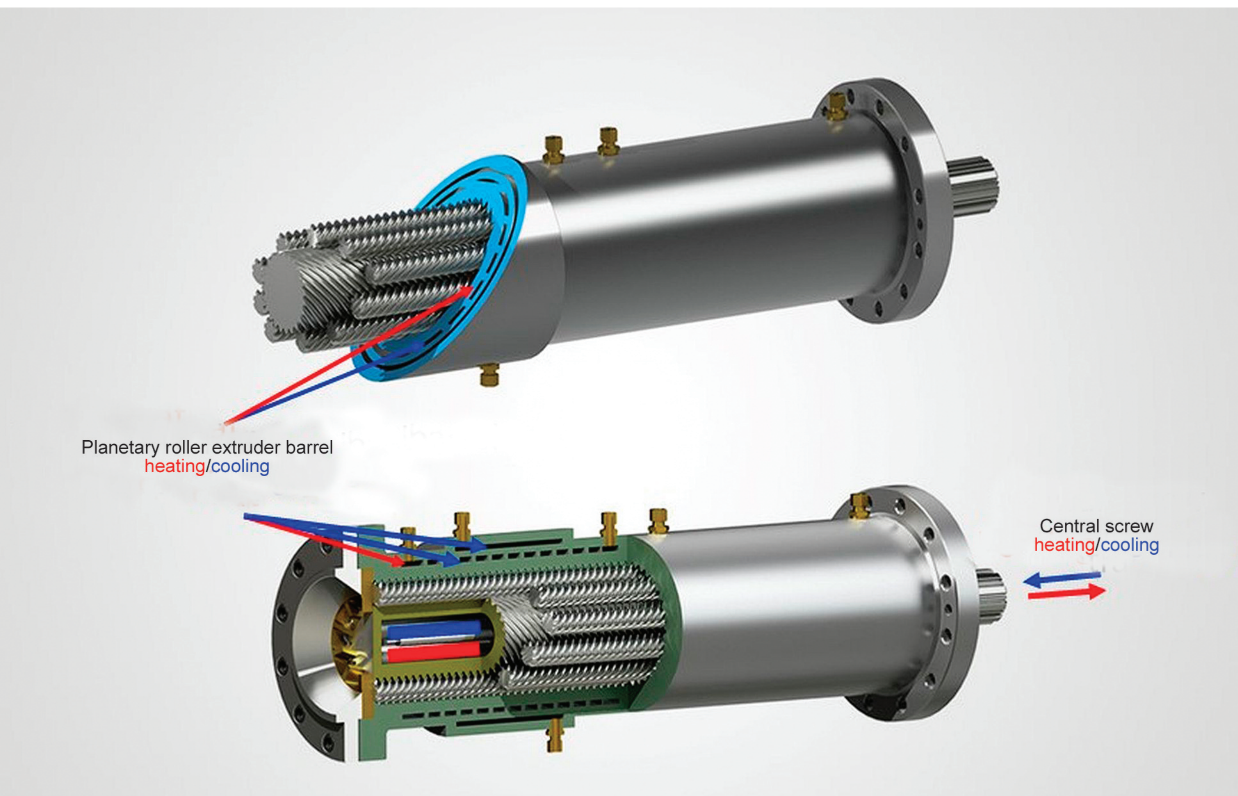


Figure 4. Heat transfer in the planetary roller extruders (adopted with permission from Takimsan Disli Kesici Ltd. Sti., İstanbul, Türkiye, https://www.takimsan.com).

materials precisely. Secondly, but more importantly, the application of electrical heaters allows for the reduction of laboratory scale machine price and laboratory space necessary for trials because, in this solution, the application of an additional temperature control system (one unit per each section of the planetary group) can be omitted. There is growing interest in laboratory-sized planetary roller extruder machines (size below 100 mm). Currently, only two companies offer this solution: Entex Rust & Mitschke GmbH (Germany) and Takimsan Disli Kesici Ltd. Sti. (Türkiye). This approach is a promising step forward for further sustainable development of planetary roller extruder-based technologies. Birr [65] demonstrates the use of planetary roller extruder technology for producing wood plastic composites (WPC) containing up to 80% wood filler by weight. The two-stage planetary roller extruder was developed by Battenfeld-Cincinnati USA, formerly American Maplan Corporation, in McPherson, Kansas, USA. It was found that a planetary roller extruder allows high dispersive mixing using low shear, which is less damaging to cellulosic and lignocellulosic fibers than the higher shear in a corotating twin-screw extruder. Moreover, the planetary roller extruder allows the processing of materials with relatively high moisture content – up to 4% [66].

The increased awareness of the compounding potential of planetary roller extruders has resulted from great success in wood plastic composite production. Nevertheless, data published in the literature on this subject still need to be improved, as shown in Table 1. The first work about experimental investigations to analyze the processing behavior of planetary roller extruders was published in 2002 by Limper *et al*. [67]. Most of this field's research has focused on the modeling of conveying and melting behavior as a function of processing parameters [68–71]. Planetary roller extrusion modeling can be a useful tool for scaling this technology. Recently, Radwan and Frerich [72] showed interesting scaling studies using two sizes of planetary roller extruders: a lab scale with an inner diameter of 30 mm – coded as PRE30 and a pilot scale with an inner diameter of 70 mm – coded as PRE70. The authors investigated and compared the planetary roller extruders' melt temperature, pressure and residence time distribution. The results related to the processing of the high-density polyethylene are presented in Figure 5. As can be observed, the deviation between both extruder sizes for melt temperature is linked to the position in the extrusion process (up to 30% at the dispersing ring (T1) and up to 15% at the nozzle (T2). The melt temperature was higher in the PRE70 (pilot plant) than in the PRE30 (lab scale). This is due to the smaller internal volume of the PRE30, which generates less shear heat. Higher melt temperature (lower material viscosity) affects the lower pressure build-up inside the planetary roller extruder [72]. Therefore, the pressure at the dispersing ring (P1) for PRE70 is lower than in PRE30, particularly at high throughputs. It was observed that the residence time increased with decreasing conveying speed and higher melt viscosity.

It should be pointed out that most planetary roller extrusion modeling procedures consider the use of pure polymers [67–69]. In contrast, in reality, polymers are often blended with other polymers or modified with suitable additives (*e.g.*, fillers, plasticizers, curing agents, *etc.*). Therefore, it would be more

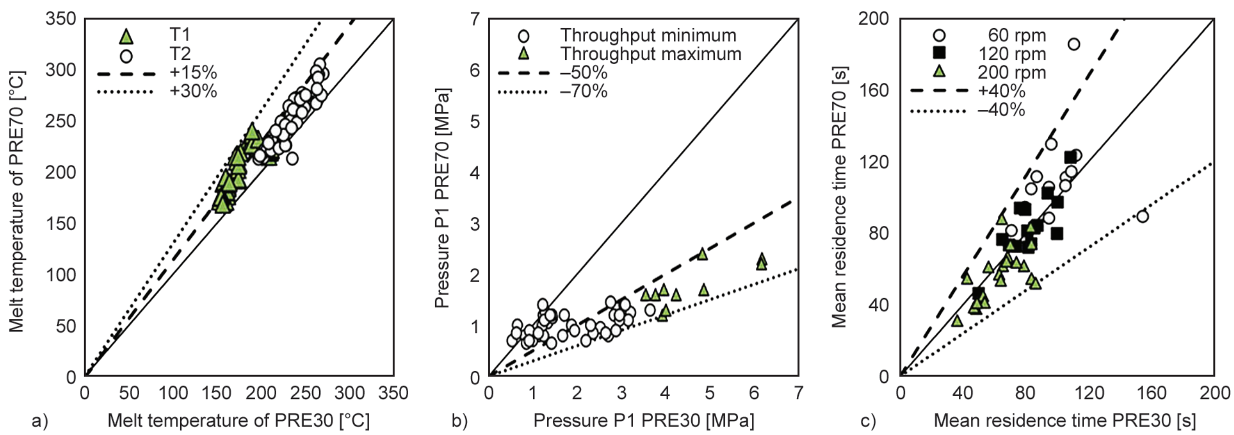


Figure 5. a) Melt temperature, b) pressure dispersing ring (P1), and c) mean residence time for lab scale (PRE30) and pilot plant (PRE70) planetary roller extruders (adopted from [72]).

informative to publish research on the effects of planetary roller extrusion conditions on extrusion outputs (*e.g.*, melt temperature, pressure, torque, specific energy consumption, residence time) and the final performance properties of the obtained products.

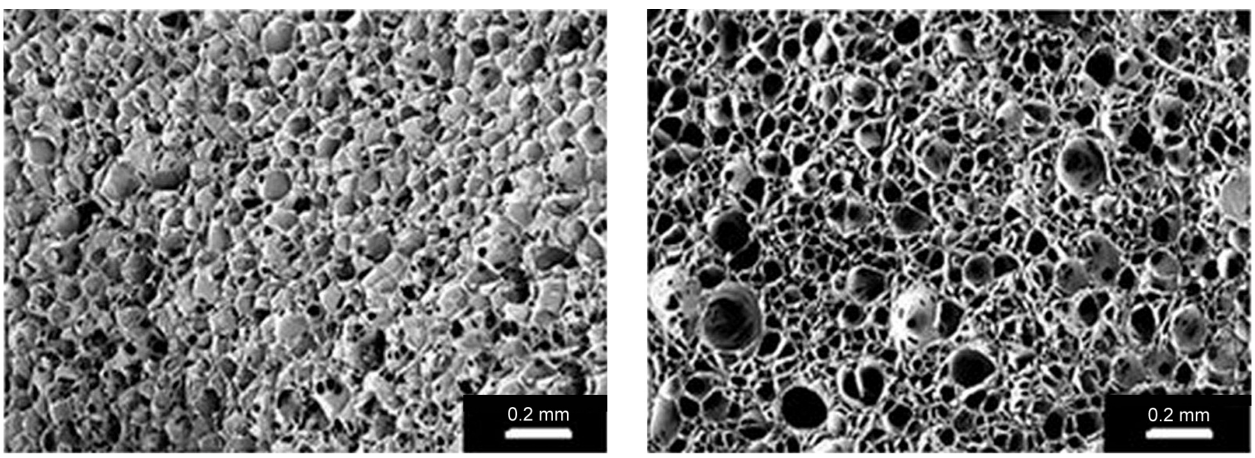
The application of planetary roller extruders is an efficient method for continuous granulation or pulverization of materials prone to thermal degradation, such as pharmaceutics [73, 74], gun propellants [75], or biopolymers [76].

Recently, Nesges *et al*. [77] suggested that planetary roller extrusion is a promising alternative for continuous melt granulation of pharmaceutical compounds based on hydroxypropyl cellulose as a melt binder (10 wt%) and lactose monohydrate. The authors indicate that the precise control of temperature in the planetary roller extruders allows for overcoming some fundamental challenges of the standard techniques for continuous granulation, indicating a need for further investigation in this field.

Ratecka [78] investigated the possibility of pulverization of polymers with a planetary roller extruder combined with a spraying process. During melt compounding, the compressed CO_2 is dissolved into a polymer matrix, which reduces the melt viscosity and improves spraying. Polymer particles are produced by atomizing the melt as the pressurized melt expands through the nozzle into the spray tower. In this step, CO_2 is released from the polymer matrix behind the nozzle, then cools the decomposing melt due to the Joule-Thomson effect, and the CO_2 content in the melt polymer is reduced from 30 to 0.9–2.2% in the solidified powder. This method is based on particles from the gas-saturated solutions (PGSS) technique, which allows the production of powders with micrometric sizes and a controlled size distribution [79]. The preliminary results showed that pulverization of highly viscous polymer melts using a planetary roller extruder could be a potential method for producing polymeric powders dedicated to selective laser sintering technology.

Another interesting option for the application of planetary roller extruders is the CO_2-assisted foaming of PLA [80–82]. This 'green' technology does not require any organic solvent. The size and distribution of pores in the PLA foams are affected by various extrusion conditions (*e.g.,* screw design, melt temperature/pressure, CO_2 content and injection pressure, *etc.*). The correlation between the foaming conditions for PLA 2003D in the planetary roller extruder and SEM images of morphologies for samples A and B were collected perpendicular to the extrusion direction is presented in Figure 6. For sample A, melt temperature and CO_2 mass fraction were 114.3 °C and 5.8 m/m %, while for sample B, values of these parameters were 104.8 °C and 10.5 m/m%, respectively. As can be noticed, the porosity of PLA foams prepared via planetary roller extrusion can exceed 95% [82].

Continuous mixing of rubber compounds is another interesting route for the application of extrusion-based



a) Sample A

b) Sample B

	Injection pressure [MPa]	Melt pressure [MPa]	Melt temperature [°C]	CO_2 mass fraction [m/m%]	Foam porosity [%]
Sample A	7.83	10.1	114.3	5.8	95.2
Sample B	9.99	9.7	104.8	10.5	96.7

Figure 6. SEM images of PLA 2003D after CO_2-assisted foaming in the planetary roller extruder at different conditions: a) sample A; b) sample B (data adopted from [82]).

technologies [83–85], which is gaining more and more attention [86–88]. However, most attempts in this field of research were mainly focused on the application of continuous mixers [89–91] and twin screw extruders [92–94]. Recently, Wu *et al*. [95] demonstrated that continuous mixing of natural rubber /carbon black nanocomposites leads to a significant reduction in energy consumption and the mixing time (up to 1.5 min) compared to traditional rubber compounding using an internal mixer. Moreover, resulting rubber composites exhibits well-dispersed morphology and high-performance properties.

Luther *et al*. [96] compared the processing and tensile properties of styrene-butadiene rubber/silica composites prepared by an internal mixer and planetary roller extruder. The results are summarized in Table 6. As can be observed, the studied rubber composites have no significant differences in the curing characteristics (determined by torque increment, $S'_{max} - S'_{min}$ parameter) and mechanical properties (tensile strength, elongation at break, hardness), regardless of the processing method used. On the other hand, the specific energy consumption for traditional batch mixing is almost 4 times higher when compared to continuous mixing by planetary roller extruder, which fully justified the further development of research works in this field.

Planetary roller extruders can be also used for waste rubber devulcanization [97]. Reactive extrusion breaks down the three-dimensional cross-linked structure in the waste rubber resulting in so-called 'reclaimed rubbers' [98]. These products are often used as a low-cost and environmentally-friendly alternative to fresh rubbers. As mentioned, planetary roller extruders can be used for both: continuous mixing of rubber compounds and further recycling of waste rubbers. This enables the design of closed-loop processes in the rubber industry, which aligning with sustainable development strategies.

Moreover, it should be highlighted that further research works focused on the continuous mixing of rubber compounds and their recycling by reactive extrusion will also affect the other technologies used in the rubber industry, such as thermoplastics/rubber blends and thermoplastic elastomers production [99] as well as the rubber functionalization techniques (*e.g.,* by grafting [100]), which are still in development.

To present the recent advances in the application of planetary roller extruders, the collection of patents and patent applications submitted between 2012 and 2023 are summarized in Table 7. The presented data were gathered on 14 July 2023 and considered terms: 'planetary roller extruder' and 'planetary extruder' in such databases as Google Patents (https://patents.google.com), Patentscope (https://patentscope.wipo.int) and Espacenet (https://worldwide.espacenet.com). Based on the examples presented in Table 7, the main fields of planetary roller extruders application can be divided into: polyvinyl chloride (*e.g.,* Guangzhou Xufa New Material Co., Ltd. (China), Jiangsu Huaxin New Material Co. Ltd. (China)); starch and biodegradable materials (*e.g.,* Battenfeld-Cincinnati Germany GmbH (Germany); Hainan Cornerstone Biotechnology Co., Ltd. (China); Green World Biotech Materials Co., Ltd. (Taiwan)); pressure sensitive adhesives (*e.g.,* Tesa SE (Germany), Intertape Polymer Corp. (USA)); polymer foams (*e.g.,* 3M Innovative Properties Company (USA), Nan Ya Plastics Corporation (USA); cellulose and wood plastic composites (*e.g.,* Re-Organic AS (Norway), Akzo Nobel Chemicals International BV (Netherlands)); synthesis and functionalization of polymers (*e.g.,* Entex Rust & Mitschke GmbH (Germany), Intertape Polymer Corp. (USA), R. Koch (Germany)); polymer stabilizers production (*e.g.,* Akdeniz Chemson Additives AG (Austria); artificial leather manufacturing (*e.g.,* Wuxi Hualian Plastic Products Co., Ltd. (China), Jiangyin Huadong Plastic

Table 6. Processing and mechanical properties for styrene-butadiene rubber/silica composites prepared by internal mixer and planetary roller extruder (data adopted from [96]).

Property		Internal mixer 1.5 l laboratory internal mixer batch (3 steps, 11 min) (~8 kg/h)	Planetary roller extruder screw diameter: 70 mm (3 moduls) continuous (40 kg/h)
Specific energy input	[kWh/kg]	1.680	0.425
$S'_{max} - S'_{min}$	[dNm]	14.5	14.9
Tensile strength	[MPa]	23.3	22.0
Elongation at break	[%]	497	616
Hardness	[Shore A]	65	65

Table 7. Recent patents and patent applications on the planetary roller extruders – examples.

Year	Patent or patent application number	Applicant	Country	Subject
2023	WO/2023/052211	Battenfeld-Cincinnati Germany GmbH	Germany	Processing of biodegradable materials
2023	WO/2023/088951	WingBeam AS	Norway	Recycling of used wind turbine blades
2023	CN116023684A	Weihai Jundao New Material Technology Co., Ltd in collaboration with Qingdao University of Science and Technology	China	Highly filled rubber compounding
2022	CN115383923	Hainan Cornerstone Biotechnology Co., Ltd.	China	Starch and biodegradable materials blends
2022	CN115141441	Jiangsu Huaxin New Material Co. Ltd.	China	Polyvinyl chloride processing
2022	WO2022254390	Rubber Conversion S.r.l.	Italy	Rubber devulcanization
2022	WO2022232319	Holcim Technology Ltd.	Switzerland	Rubber membranes manufacturing
2022	CN115505223	Jiangsu Dahai Plastic Co., Ltd., in collaboration with Jiangsu Houbang Industrial Co Ltd. and Nanjing Tech University	China	Polyvinyl chloride processing
2022	US202203805679	3M Innovative Properties Company	USA	Polymer foaming in supercritical conditions
2022	WO/2022/192928	Akdeniz Chemson Additives AG	Austria	Production of stabilizers for a polymers
2022	CN215849853	Jiangxi Chunguang New Materials Technology Co., Ltd.	China	Production of solid medicinal hard tablets
2022	CN115286868	Wuxi Hongyi Polymer Material Technology Co., Ltd	China	Polypropylene processing at low temperatures
2022	WO/2022/033743	Re-Organic AS	Norway	Nanocellulose-based composite preparation
2022	P.437464	Recykl Organizacja Odzysku S.A.	Poland	Rubber devulcanization
2022	P.437463	Recykl Organizacja Odzysku S.A.	Poland	Rubber recycling
2021	EP3790718	Tesa SE	Germany	Adhesive glue
2020	EP3714001	Tesa SE	Germany	Production of pressure-sensitive reactive adhesive tapes
2020	US20200048436	Green World Biotech Materials Co., Ltd.	Taiwan	Hydrophobic thermoplastic starch composite
2020	EP3672773	Tesa SE	Germany	Production of thermally cross-linkable polymer melts
2020	CN211390081	Suzhou Reachlong New Materials Co., Ltd.	China	Polyvinyl chloride processing
2020	CN110947985	Nan Ya Plastics Corporation	USA	Foamed polyvinyl chloride manufacturing
2020	WO/2020/038598	Entex Rust & Mitschke GmbH in collaboration with Novo-Tech GmbH & Co. KG	Germany	Manufacturing of wood plastic composites
2020	P.428405	Recykl Organizacja Odzysku S.A.	Poland	Rubber devulcanization
2019	DE102019105335	R. Koch	Germany	Polymerization of polylactide
2018	DE102016010082	Entex Rust & Mitschke GmbH	Germany	Polyvinyl chloride processing
2018	CN108070251	Jiangyin Yonglong Plastic Co., Ltd.	China	Semi-aromatic polyamide artificial leather
2018	CN108481697	Guangzhou Xufa New Material Co., Ltd.	China	Polyvinyl chloride processing
2017	DE102016007290	Entex Rust & Mitschke GmbH	Germany	Rubber devulcanization
2017	CN106700501	Wuxi Hualian Plastic Products Co., Ltd.	China	Aliphatic polyamide artificial leather
2017	CN106700492	Jiangyin Huadong Plastic Products Co., Ltd.	China	Polyurethane artificial leather
2017	EP3173162	Continental Reifen Deutschland GmbH	Germany	Rubber devulcanization
2016	CN106167591	Taicang All Mats Plastic. Industry Co., Ltd.	China	Polyvinyl chloride foams production
2015	CN104356555	Tianjin Tiansu Technology Group Co., Ltd.	China	Polyvinyl chloride processing
2015	EP2838373	Intercontinental Great Brands LLC	USA	Chewing gum manufacturing
2015	US20150152207	Intertape Polymer Corp.	USA	Continuous bulk polymerization of vinyl monomers
2015	EP2828077	Firestone Building Products LLC	USA	Rubber membranes production
2014	US20140011945	Intertape Polymer Corp.	USA	Pressure sensitive adhesive manufacturing
2013	EP2593603	Akzo Nobel Chemicals International BV	Netherlands	Cellulose fibers treatment (paper manufacturing)
2012	DE102010025995	Entex Rust & Mitschke GmbH	Germany	Synthesis of thermoplastic polyurethanes
2012	DE102010030706	Entex Rust & Mitschke GmbH	Germany	Chemical modification of polymers or waxes

Products Co., Ltd. (China)); rubber compounding (*e.g.,* Holcim Technology Ltd. (Austria), Firestone Building Products LLC (USA), Intercontinental Great Brands LLC (USA)) ; polymer and rubber recycling (*e.g.,* WingBeam AS (Norway), Recykl Organizacja Odzysku S.A. (Poland), Continental Reifen Deutschland GmbH (Germany)).

As can be observed, many patent applications related to using planetary roller extruders have been submitted in the last three years, which clearly indicates enormous potential for further development of this technology in the near future.

5. Conclusions

Melt-compounding and reactive extrusion are currently some of the most promising processing methods for the preparation of new polymer blends and composites. The main advantages of planetary roller extruders are excellent distributive mixing and reduced energy consumption compared to commonly used single-screw and twin-screw extruders. On the other hand, the main disadvantage of planetary roller extruders compared to other screw extruders is related to the high costs of their purchase and further maintenance (plasticizing unit regeneration/modernization).

The recent development of the planetary roller extruder laboratory-size machines (and increasing access to this solution) is a huge step forward to the upscaling and industrial application of planetary roller extruder-based technologies.

The state of knowledge presented in this paper indicates that nowadays, sustainable development of polymer engineering using a planetary roller extruders involved: i) thermal sensitive and biodegradable polymeric materials (*e.g.*, food packages, pharmaceutics, wood plastic composites, tissue engineering, *etc.*); ii) high-viscous systems processing (*e.g.*, rubber goods, adhesives, sealants); iii) 3D printing materials (*e.g.*, filaments, powders); iv) reactive extrusion, modification and/or functionalization of polymers (*e.g.*, grafting, compatibilization, *etc.*) and v) plastics and rubbers recycling (*e.g.*, devulcanization, pyrolysis). However, it should be noted that this classification is still open, and with further development of reactive extrusion technologies in organic synthesis, the number of applications of planetary roller extruders in various branches of the industry should continue to grow in the near future.

Recent trends showed that further investigations on the application of planetary roller extruders in polymer chemistry and engineering should focus on two main directions. First, all aspects related to energy-saving process parameters (*e.g.*, modification of screws construction, screw configuration or extrusion die, barrel design to improve heat transfer, *etc.*) and lower content of used additives (*e.g.*, plasticizers, stabilators, *etc.*) in the final formulation should be considered, which allow an overall significant reduction of the production costs. The second direction should be focused on the relationship between planetary roller extruder design, extrusion conditions, and the final properties of obtained materials. This approach includes further analysis and optimization of the processing parameters, which increases the efficiency of the process and simplifies the further implementation of laboratory results to industrial scale.

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References

[1] Vieyra H., Molina-Romero J. M., de Dios Calderón-Nájera J., Santana-Díaz A.: Engineering, recyclable, and biodegradable plastics in the automotive industry: A review. Polymers, **14**, 3412 (2022). https://doi.org/10.3390/polym14163412

[2] Pires P. C., Mascarenhas-Melo F., Pedrosa K., Lopes D., Lopes J., Macário-Soares A., Peixoto D., Giram P. S., Veiga F., Paiva-Santos A. C.: Polymer-based biomaterials for pharmaceutical and biomedical applications: A focus on topical drug administration. European Polymer Journal, **187**, 111868 (2023). https://doi.org/10.1016/j.eurpolymj.2023.111868

[3] Zhang M., Biesold G. M., Choi W., Yu J., Deng Y., Silvestre C., Lin Z.: Recent advances in polymers and polymer composites for food packaging. Materials Today, **53**, 134–161 (2022). https://doi.org/10.1016/j.mattod.2022.01.022

[4] González-Henríquez C. M., Sarabia-Vallejos M. A., Rodriguez-Hernandez J.: Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications. Progress in Polymer Science, **94**, 57–116 (2019). https://doi.org/10.1016/j.progpolymsci.2019.03.001

[5] Ma H., Gao B., Wang M., Yuan Z., Shen J., Zhao J., Feng Y.: Strategies for enhancing thermal conductivity of polymer-based thermal interface materials: A review. Journals of Materials Science, **56**, 1064–1086 (2021). https://doi.org/10.1007/s10853-020-05279-x

[6] Vlachopoulos J., Strutt D.: Polymer processing. Materials Science and Technology, **19**, 1161–1169 (2003). https://doi.org/10.1179/026708303225004738
[7] Sakai T.: Screw extrusion technology – Past, present and future. Polimery, **58**, 847–857 (2013). https://doi.org/10.14314/polimery.2013.847
[8] Hyvärinen M., Jabeen R., Kärki T.: The modelling of extrusion processes for polymers – A review. Polymers, **12**, 1306 (2020). https://doi.org/10.3390/polym12061306
[9] Wilczyński K., Nastaj A., Lewandowski A., Wilczyński K. J., Buziak K.: Fundamentals of global modeling for polymer extrusion. Polymers, **11**, 2106 (2019). https://doi.org/10.3390/polym11122106
[10] Villmow T., Kretzschmar B., Pötschke P.: Influence of screw configuration, residence time, and specific mechanical energy in twin-screw extrusion of polycaprolactone/multi-walled carbon nanotube composites. Composites Science and Technology, **70**, 2045–2055 (2010). https://doi.org/10.1016/j.compscitech.2010.07.021
[11] Calderón B. A., McCaughey M. S., Thompson C. W., Barinelli V. L., Sobkowicz M. J.: Evaluating the influence of specific mechanical energy on biopolymer blends prepared via high-speed reactive extrusion. ACS Applied Polymer Materials, **1**, 1410–1419 (2019). https://doi.org/10.1021/acsapm.9b00177
[12] Kaczor D., Bajer K., Raszkowska-Kaczor A., Domek G., Madajski P., Szroeder P.: The influence of multiple extrusions on the properties of high filled polylactide/multiwall carbon nanotube composites. Materials, **15**, 8958 (2022). https://doi.org/10.3390/ma15248958
[13] Vaidya A. A., Gaugler M., Smith D. A.: Green route to modification of wood waste, cellulose and hemicellulose using reactive extrusion. Carbohydrate Polymers, **136**, 1238–1250 (2016). https://doi.org/10.1016/j.carbpol.2015.10.033
[14] Hejna A., Barczewski M., Skórczewska K., Szulc J., Chmielnicki B., Korol J., Formela K.: Sustainable upcycling of brewers' spent grain by thermo-mechanical treatment in twin-screw extruder. Journal of Cleaner Production, **285**, 124839 (2021). https://doi.org/10.1016/j.jclepro.2020.124839
[15] Guiao K. S., Gupta A., Tzoganakis C., Mekonnen T. H.: Reactive extrusion as a sustainable alternative for the processing and valorization of biomass components. Journal of Cleaner Production, **355**, 131840 (2022). https://doi.org/10.1016/j.jclepro.2022.131840
[16] Yang X., Clénet J., Xu H., Odelius K., Hakkarainen M.: Two step extrusion process: From thermal recycling of PHB to plasticized PLA by reactive extrusion grafting of PHB degradation products onto PLA chains. Macromolecules, **48**, 2509–2518 (2015). https://doi.org/10.1021/acs.macromol.5b00235
[17] Shi J., Zou H., Ding L., Li X., Jiang K., Chen T., Zhang X., Zhang L., Ren D.: Continuous production of liquid reclaimed rubber from ground tire rubber and its application as reactive polymeric plasticizer. Polymer Degradation and Stability, **99**, 166–175 (2014). https://doi.org/10.1016/j.polymdegradstab.2013.11.010
[18] Zedler Ł., Wang S., Formela K.: Ground tire rubber functionalization as a promising approach for the production of sustainable adsorbents of environmental pollutants. Science of the Total Environment, **836**, 155636 (2022). https://doi.org/10.1016/j.scitotenv.2022.155636
[19] Bolt R. R. A., Leitch J. A., Jones A. C., Nicholson W. I., Browne D. L.: Continuous flow mechanochemistry: Reactive extrusion as an enabling technology in organic synthesis. Chemical Society Reviews, **51**, 4243–4260 (2022). https://doi.org/10.1039/D1CS00657F
[20] Ortiz-Rodriguez E., Tzoganakis C.: Scaling-up a reactive extrusion operation: A one-dimensional simulation analysis. International Polymer Processing, **25**, 242–250 (2010). https://doi.org/10.3139/217.2346
[21] Nastaj A., Wilczyński K.: Optimization and scale-up for polymer extrusion. Polymers, **13**, 1547 (2021). https://doi.org/10.3390/polym13101547
[22] Arora B., Yoon A., Sriram M., Singha P., Rizvi S. S. H.: Reactive extrusion: A review of the physicochemical changes in food systems. Innovative Food Science and Emerging Technologies, **64**, 102429 (2020). https://doi.org/10.1016/j.ifset.2020.102429
[23] Bamidele O. P., Emmambux M. N.: Encapsulation of bioactive compounds by 'extrusion' technologies: A review. Critical Reviews in Food Science Nutrition, **61**, 3100–3118 (2021). https://doi.org/10.1080/10408398.2020.1793724
[24] Prabha K., Ghosh P., Abdullah S., Joseph R. M., Krishnan R., Rana S. S., Pradhan R. A.: Recent development, challenges, and prospects of extrusion technology. Future Foods, **3**, 100019 (2021). https://doi.org/10.1016/j.fufo.2021.100019
[25] Patil H., Tiwari R. V., Repka M. A.: Hot-melt extrusion: From theory to application in pharmaceutical formulation. AAPS PharmSciTech, **17**, 20–42 (2016). https://doi.org/10.1208/s12249-015-0360-7
[26] Crawford D. E., Porcheddu A., McCalmont A. S., Delogu F., James S. L., Colacino E.: Solvent-free, continuous synthesis of hydrazone-based active pharmaceutical ingredients by twin-screw extrusion. ACS Sustainable Chemistry and Engineering, **8**, 12230–12238 (2020). https://doi.org/10.1021/acssuschemeng.0c03816
[27] Zupančič O., Spoerk M., Paudel A.: Lipid-based solubilization technology *via* hot melt extrusion: Promises and challenges. Expert Opinion Drug Delivery, **19**, 1013–1032 (2022). https://doi.org/10.1080/17425247.2022.2112173

[28] Formela K., Zedler Ł., Hejna A., Tercjak A.: Reactive extrusion of bio-based polymer blends and composites – Current trends and future developments. Express Polymer Letters, **12**, 24–57 (2018). https://doi.org/10.3144/expresspolymlett.2018.4

[29] Przybysz-Romatowska M., Haponiuk J., Formela K.: Reactive extrusion of biodegradable aliphatic polyesters in the presence of free-radical-initiators: A review. Polymer Degradation Stability, **182**, 109383 (2020). https://doi.org/10.1016/j.polymdegradstab.2020.109383

[30] Edeleva M., de Smit K., Debrie S., Verberckmoes A., Marien Y. W., D'hooge D. R.: Molecular scale-driven upgrading of extrusion technology for sustainable polymer processing and recycling. Current Opinion in Green and Sustainable Chemistry, **43**, 100848 (2023). https://doi.org/10.1016/j.cogsc.2023.100848

[31] Varghese R., Sood P., Salvi S., Karsiya J., Kumar D.: 3D printing in the pharmaceutical sector: Advances and evidences. Sensors International, **3**, 100177 (2022). https://doi.org/10.1016/j.sintl.2022.100177

[32] Zhang J., Li Y., Cai Y., Ahmad I., Zhang A., Ding Y., Qiu Y., Zhang G., Tang W., Lyu F.: Hot extrusion 3D printing technologies based on starchy food: A review. Carbohydrate Polymers, **294**, 119763 (2022). https://doi.org/10.1016/j.carbpol.2022.119763

[33] Herzberger J., Sirrine J. M., Williams C. B., Long T. E.: Polymer design for 3D printing elastomers: Recent advances in structure, properties, and printing. Progress in Polymer Science, **97**, 101144 (2019). https://doi.org/10.1016/j.progpolymsci.2019.101144

[34] Alshahrani H. A.: Review of 4D printing materials and reinforced composites: Behaviors, applications and challenges. Journal of Science: Advanced Materials and Devices, **6**, 167–185 (2021). https://doi.org/10.1016/j.jsamd.2021.03.006

[35] Ryan K. R., Down M. P., Hurst N. J., Keefe E. M., Banks C. E.: Additive manufacturing (3D printing) of electrically conductive polymers and polymer nanocomposites and their applications. eScience, **2**, 365–381 (2022). https://doi.org/10.1016/j.esci.2022.07.003

[36] Ameta K. L., Solanki V. S., Singh V., Devi A. P., Chundawat R. S., Haque S.: Critical appraisal and systematic review of 3D & 4D printing in sustainable and environment-friendly smart manufacturing technologies. Sustainable Materials Technology, **34**, e00481 (2022). https://doi.org/10.1016/j.susmat.2022.e00481

[37] Imre B., Pukánszky B.: Compatibilization in bio-based and biodegradable polymer blends. European Polymer Journal, **49**, 1215–1233 (2013). https://doi.org/10.1016/j.eurpolymj.2013.01.019

[38] Zhao X., Hu H., Wang X., Yu X., Zhou W., Peng S.: Super tough poly(lactic acid) blends: A comprehensive review. RSC Advances, **10**, 13316–13368 (2020). https://doi.org/10.1039/D0RA01801E

[39] Dorigato A.: Recycling of polymer blends. Advanced Industrial and Engineering Polymer Research, **2**, 53–69 (2021). https://doi.org/10.1016/j.aiepr.2021.02.005

[40] Vahabi H., Laoutid F., Formela K., Saeb M. R., Dubois P.: Flame-retardant polymer materials developed by reactive extrusion: Present status and future perspectives. Polymer Reviews, **62**, 919–949 (2022). https://doi.org/10.1080/15583724.2022.2052897

[41] de Smit K., Wieme T., Marien Y. W., van Steenberge P. H. M., D'hooge D. R., Edeleva M.: Multi-scale reactive extrusion modelling approaches to design polymer synthesis, modification and mechanical recycling. Reaction Chemistry and Engineering, **7**, 245–263 (2022). https://doi.org/10.1039/D1RE00556A

[42] Phiri M. M., Phiri M. J., Formela K., Wang S., Hlangothi S. P.: Grafting and reactive extrusion technologies for compatibilization of ground tyre rubber composites: Compounding, properties, and applications. Journal of Cleaner Production, **369**, 133084 (2022). https://doi.org/10.1016/j.jclepro.2022.133084

[43] Gaudino E. C., Grillo G., Manzoli M., Tabasso S., Maccagnan S., Cravotto G.: Mechanochemical applications of reactive extrusion from organic synthesis to catalytic and active materials. Molecules, **27**, 449 (2022). https://doi.org/10.3390/molecules27020449

[44] Andersen J., Starbuck H., Current T., Martin S., Mack J.: Milligram-scale, temperature-controlled ball milling to provide an informed basis for scale-up to reactive extrusion. Green Chemistry, **23**, 8501–8509 (2021). https://doi.org/10.1039/d1gc02174e

[45] Leitch J. A., Richardson P., Browne D. L.: Evolution of solid processing methods in continuous flow technology: Reactive extrusion. CHIMIA, **77**, 339–345 (2023). https://doi.org/10.2533/chimia.2023.339

[46] Crawford D., Casaban J., Haydon R., Giri N., McNally T., James S. L.: Synthesis by extrusion: Continuous, large-scale preparation of MOFs using little or no solvent. Chemical Science, **6**, 1645–1649 (2015). https://doi.org/10.1039/C4SC03217A

[47] Gomollón-Bel F.: Ten chemical innovations that will change our world: IUPAC identifies emerging technologies in chemistry with potential to make our planet more sustainable. Chemistry International, **41**, 12–17 (2019). https://doi.org/10.1515/ci-2019-0203

[48] Xu E., Campanella O. H., Ye H., Jin Z., Liu D., BeMiller J. N.: Advances in conversion of natural biopolymers: A reactive extrusion (REX)–enzyme-combined strategy for starch/protein-based food processing. Trends in Food Science and Technology, **99**, 167–180 (2020). https://doi.org/10.1016/j.tifs.2020.02.018

[49] Quan Y., Shen R., Ma R., Zhang Z., Wang Q.: Sustainable and efficient manufacturing of metal-organic framework-based polymer nanocomposites by reactive extrusion. ACS Sustainable Chemistry and Engineering, **10**, 7216–7222 (2022). https://doi.org/10.1021/acssuschemeng.2c01720

[50] Li T-T., Cheng S-B., Feng L-F., Gu X-P., Duan J-T., Jiang M-Z., Zhang C-L.: A review on the free radical grafting of vinyl monomers onto polyethylene and polypropylene by reactive extrusion. Chemical Engineering Science, **278**, 118916 (2023). https://doi.org/10.1016/j.ces.2023.118916

[51] Tzoganakis C.: Reactive extrusion of polymers: A review. Advances in Polymer Technology, **9**, 321–330 (1989). https://doi.org/10.1002/adv.1989.060090406

[52] Wu F., Misra M., Mohanty A. K.: Sustainable green composites from biodegradable plastics blend and natural fibre with balanced performance: Synergy of nano-structured blend and reactive extrusion. Composites Science and Technology, **200**, 108369 (2020). https://doi.org/10.1016/j.compscitech.2020.108369

[53] Ozdemir E., Arenas D. R., Kelly N. L., Hanna J. V., van Rijswijk B., Degirmenci V., McNally T.: Ethylene methyl acrylate copolymer (EMA) assisted dispersion of few-layer graphene nanoplatelets (GNP) in poly (ethylene terephthalate) (PET). Polymer, **205**, 122836 (2020). https://doi.org/10.1016/j.polymer.2020.122836

[54] Tang Q., Wang K., Ren X., Zhang Q., Lei W., Jiang T., Shi D.: Preparation of porous antibacterial polyamide 6 (PA6) membrane with zinc oxide (ZnO) nanoparticles selectively localized at the pore walls *via* reactive extrusion. Science of the Total Environment, **715**, 137018 (2020). https://doi.org/10.1016/j.scitotenv.2020.137018

[55] Li K., Xiang J., Zhou J., Su X., Xie H., Lin S., Xiao Z., Huang W., Zhao C., Chen H., Wu W.: Self-healing and wear resistance stable superhydrophobic composite coating with electrothermal and photothermal effects for anti-icing. Progress in Organic Coatings, **177**, 107415 (2023). https://doi.org/10.1016/j.porgcoat.2023.107415

[56] Bäckström E., Odelius K., Hakkarainen M.: Designed from recycled: Turning polyethylene waste to covalently attached polylactide plasticizers. ACS Sustainable Chemistry and Engineering, **7**, 11004–11013 (2019). https://doi.org/10.1021/acssuschemeng.9b02092

[57] Wiśniewska P., Haponiuk J., Colom X., Saeb M. R.: Green approaches in rubber recycling technologies: Present status and future perspective. ACS Sustainable Chemistry and Engineering, **11**, 8706–8726 (2023). https://doi.org/10.1021/acssuschemeng.3c01314

[58] Jehanno C., Alty J. W., Roosen M., de Meester S., Dove A. P., Chen E. Y-X., Leibfarth F. A., Sardon H.: Critical advances and future opportunities in upcycling commodity polymers. Nature, **603**, 803–814 (2022). https://doi.org/10.1038/s41586-021-04350-0

[59] Crawford D. E.: Extrusion – Back to the future: Using an established technique to reform automated chemical synthesis. Beilstein Journal of Organic Chemistry, **13**, 65–75 (2017). https://doi.org/10.3762/bjoc.13.9

[60] Mount E. M.: Extrusion processes. in 'Applied plastics engineering handbook: Processing, materials, and applications' (ed.: Kutz M.) Elsevier, Kidlington, 217–264 (2017).

[61] Utracki L. A., Shi G. Z. H.: Compounding polymer blends. in 'Polymer blends handbook' (ed.: Utracki L. A.) Springer, Dordrecht, 577–651 (2003).

[62] Rauwendaal C.: Mixing in single screw extruders. in 'Mixing in polymer processing' (ed.: Rauwendaal C.) Marcel Dekker, New York, 129–240 (1991).

[63] Kent R.: Energy management in plastics processing – Framework for measurement, assessment and prediction. Plastics, Rubber and Composites, **37**, 96–104 (2008). https://doi.org/10.1179/174328908X283285

[64] Vera-Sorroche J., Kelly A., Brown E., Coates P., Karnachi N., Harkin-Jones E., Li K., Deng J.: Thermal optimisation of polymer extrusion using in-process monitoring techniques. Applied Thermal Engineering, **53**, 405–413 (2013). https://doi.org/10.1016/j.applthermaleng.2012.04.013

[65] Birr T.: Processing of long glass fiber reinforced thermoplastics for injection molding applications on the planetary roller extruder (in German). PhD Thesis, Technischen Universität Berlin (2016). https://doi.org/10.14279/depositonce-5116

[66] Markarian J.: Wood-plastic composites: Current trends in materials and processing. Plastics, Additives and Compounding, **7**, 20–26 (2005). https://doi.org/10.1016/S1464-391X(05)70453-0

[67] Limper A., Seibel S., Fattmann G.: Compounding unit planetary roller extruder. Macromolecular Materials and Engineering, **287**, 815–823 (2002). https://doi.org/10.1002/mame.200290011

[68] Rudloff J., Bastian M., Heidemeyer P., Kretschmer K.: Modelling of planetary roller extruders (in German). Kunststoffe International, **6**, 55–58 (2011).

[69] Rudloff J., Lang M., Kretschmer K., Heidemeyer P., Bastian M., Koch M.: A mathematical model describing the solid conveying and melting behavior of planetary roller extruders. AIP Conference Proceedings, **1593**, 592 (2014). https://doi.org/10.1063/1.4873850

[70] Rudloff J., Lang M., Kretschmer K., Heidemeyera P., Bastian M., Koch M.: Analysis of pellet diameter and inorganic filler influences on the polymer melting behavior in planetary roller extruders. AIP Conference Proceedings, **1914**, 080001 (2017). https://doi.org/10.1063/1.5016741

[71] Winck J., Frerich S.: Numerical simulation of fluid flow and mixing dynamics inside planetary roller extruders. International Polymer Processing, **36**, 508–518 (2021). https://doi.org/10.1515/ipp-2020-4084

[72] Radwan M., Frerich S. C.: Experimental study on the scalability of planetary roller extruders. Chemical Engineering and Technology, **46**, 1149–1155 (2023). https://doi.org/10.1002/ceat.202200523

[73] Vervaet C., Remon J. P.: Continuous granulation in the pharmaceutical industry. Chemical Engineering Science, **60**, 3949–3957 (2005). https://doi.org/10.1016/j.ces.2005.02.028

[74] Lang T., Bramböck A., Thommes M., Bartsch J.: Material transport characteristics in planetary roller melt granulation. Pharmaceutics, **15**, 2039 (2023). https://doi.org/10.3390/pharmaceutics15082039

[75] Müller D.: Procedures for the production of gun propellants by use of different extruders. Journal of Hazardous Materials, **7**, 169–186 (1983). https://doi.org/10.1016/0304-3894(83)80009-0

[76] Stahn T., Storandt R., Grebenteuch S., Rohn S., May D., Dolsdorf C., Pleissner D.: Utilization of brewer's spent grains and agricultural residues in pig feed formation. Sustainability, **15**, 13774 (2023). https://doi.org/10.3390/su151813774

[77] Nesges D., Lang T., Birr T., Thommes M., Bartsch J.: Planetary roller melt granulation (PRMG) – A new continuous method for powder processing. Powder Technology, **427**, 118728 (2023). https://doi.org/10.1016/j.powtec.2023.118728

[78] Ratecka A.: Pulverization of highly viscous polymer melts with a planetary roller extruder for selective laser sintering. in 'The European Summer School in High Pressure Technology. University of Maribor and Graz University of Technology (ESS-HPT 2019), Graz, Austria' 98–101 (2019).

[79] Tutek K., Masek A., Kosmalska A., Cichosz S.: Application of fluids in supercritical conditions in the polymer industry. Polymers, **13**, 729 (2021). https://doi.org/10.3390/polym13050729

[80] Kleinschnittger O.: Digitalisation and remote control of a planetary roller extruder for use in the PGSS and foaming processes with compressed carbon dioxide. in 'The European Summer School in High Pressure Technology. University of Maribor and Graz University of Technology (ESS-HPT 2019), Graz, Austria' 36–39 (2019).

[81] Frerich S. C.: Virtualization of process engineering – Experimental technology in teaching (in German). Chemie Ingenieur Technik, **93**, 1887–1897 (2021). https://doi.org/10.1002/cite.202100169

[82] Milovanovic S., Lukic I., Horvat G., Novak Z., Frerich S., Petermann M., García-González C. A.: Green processing of neat poly(lactic acid) using carbon dioxide under elevated pressure for preparation of advanced materials: A review (2012–2022). Polymers, **15**, 860 (2023). https://doi.org/10.3390/polym15040860

[83] Boguslawski J. J.: Basic fundamentals of extrusion and mixing theory. Rubber Chemistry and Technology, **45**, 1421–1433 (1972). https://doi.org/10.5254/1.3544749

[84] Isayev A. I., Hong C. K., Kim K. J.: Continuous mixing and compounding of polymer/filler and polymer/polymer mixtures with the aid of ultrasound. Rubber Chemistry and Technology, **76**, 923–947 (2003). https://doi.org/10.5254/1.3547782

[85] Ojogbo E., Tzoganakis C., Mekonnen T. H.: Effect of extrusion, batch-mixing, and *co*-coagulation on the dispersion of CNCs in natural rubber – CNC nanocomposites. Composites Part A: Applied Science and Manufacturing, 149, 106580 (2021). https://doi.org/10.1016/j.compositesa.2021.106580

[86] Zhu D., Wang C., Xiao Y., Wang X., Han S., Wang Z., Bian H.: Studying the continuous wet mixing process based on the silica formula. Journal of Applied Polymer Science, **138**, 50726 (2021). https://doi.org/10.1002/app.50726

[87] Sui Y., Lai Q., Nie W., Tang S., Wang C., Bian H.: Wet continuous mixing technique based on full formula of carbon black. Journal of Applied Polymer Science, **139**, e52971 (2022). https://doi.org/10.1002/app.52971

[88] Wang K., Han D., Xiao X., Wang L., Niu G., Zhang S., Wang C., Bian H.: Influence of process parameters of a continuous final mixer on the properties of carbon black/rubber composites. International Polymer Processing, **38**, 133–144 (2023). https://doi.org/10.1515/ipp-2022-4265

[89] White J. L., Liu D., Bumm S. H.: Development of dispersion in rubber-particle compounds in internal and continuous mixers. Journal of Applied Polymer Science, **102**, 3940–3943 (2006). https://doi.org/10.1002/app.24241

[90] Zhu L., Tian X., Pan Y., Chang T., Wang K., Niu G., Zhang L., Wang C., Han W.: Optimization of serial modular continuous mixing process parameters for natural rubber composites reinforced by silica/carbon black. Polymers, **12**, 416 (2020). https://doi.org/10.3390/polym12020416

[91] Zhu L., Pan Y., Tian X., Liu H., Bian H., Wang C.: Continuous preparation and properties of silica/rubber composite using serial modular mixing. Materials, **12**, 3118 (2019). https://doi.org/10.3390/ma12193118

[92] Amash A., Bogun M., Schuster R-H., Görl U., Schmitt M.: New concepts for continuous mixing of powder rubber. Plastics, Rubber and Composites, **30**, 401–405 (2001).
https://doi.org/10.1179/146580101101541796

[93] Luther S., Bogun M., Schuster R-H., Görl U.: Experimental study of the rubber mixing process using a corotating twin screw extruder. KGK Kautschuk Gummi Kunststoffe, **59**, 473–478 (2006).

[94] Yazıcı N., Kodal M., Özkoç G.: Lab-scale twin-screw micro-compounders as a new rubber-mixing tool: 'A comparison on EPDM/carbon black and EPDM/silica composites'. Polymers, **13**, 4391 (2021).
https://doi.org/10.3390/polym13244391

[95] Wu H., Lu X., He Y., Qu J-P.: Continuous mixing process and properties of NR/CB nanocomposites based on elongational rheology. Composites Part B: Engineering, **234**, 109705 (2022).
https://doi.org/10.1016/j.compositesb.2022.109705

[96] Luther S., Bogun M., Rust H.: Continuous mixing of silica filled rubber mixtures with a planetary roller extruder. KGK Kautschuk Gummi Kunststoffe, **58**, 371–375 (2005).

[97] Dierkes W., Saiwari S.: Regeneration and devulcanization. in 'Tire waste and recycling' (eds.: Letcher T. M., Shulman V. L., Amirkhanian S.) Academic Press, Cambridge, Massachusetts, 97–144 (2021).
https://doi.org/10.1016/B978-0-12-820685-0.00006-5

[98] Wiśniewska P., Wang S., Formela K.: Waste tire rubber devulcanization technologies: State-of-the-art, limitations and future perspectives. Waste Management, **150**, 174–184 (2022).
https://doi.org/10.1016/j.wasman.2022.07.002

[99] Formela K.: Strategies for compatibilization of polymer/waste tire rubber systems prepared via melt-blending. Advanced Industrial and Engineering Polymer Research, in press (2024).
https://doi.org/10.1016/j.aiepr.2023.08.001

[100] Nuinu P., Srichan S., Ngamlerd A., Wichian C., Prasertsri S., Saengsuwan S., Hinchiranan N., Vudjung C.: Preparation of environment-friendly hydrophilic rubber from natural rubber grafted with sodium acrylate by reactive melt mixing. Polymer Engineering and Science, **62**, 1833–1846 (2022).
https://doi.org/10.1002/pen.25968