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POLIMERY

Multi-screw extruders – an overview

Krzysztof Formela[1), 2), *)] (ORCID ID: 0000-0003-0867-9794), **Agata Rodak**[1), 2)] (0009-0005-6026-5494), **Adrian Bartnicki**[3)] (0000-0003-2464-5084), **Barış Eyigöz**[4)]

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Abstract: Screw extrusion is a cost-effective and solvent-free method for manufacturing polymer blends and composites. This article reviews the latest developments in the field of multi-screw extruders, i.e. triple-screw, quad-screw, octa-screw, ring, planetary and multi-rotation system (MRS). The authors also discussed limitations and directions of multi-screw extruders development.

Keywords: melt-compounding, reactive extrusion, recycling, multi-screw extruders.

Wytłaczarki wieloślimakowe – przegląd literatury

Streszczenie: Wytłaczanie ślimakowe jest ekonomiczną i bezrozpuszczalnikową metodą wytwarzania mieszanin polimerowych i kompozytów. Niniejszy artykuł stanowi przegląd najnowszych osiągnięć w zakresie wytłaczarek wieloślimakowych tj. trójślimakowych, czteroślimakowych, ośmioślimakowych, pierścieniowych i planetarnych oraz systemu MRS. Omówiono również ograniczenia i kierunki rozwoju wytłaczarek wieloślimakowych.

Słowa klucze: mieszanie w stanie stopionym, wytłaczanie reaktywne, recykling, wytłaczarki wieloślimakowe.

In 2019, the International Union of Pure and Applied Chemistry (IUPAC) identifies reactive extrusion along with flow chemistry among the top ten emerging technologies in chemistry with the potential to make our planet more sustainable [1]. Screw extrusion is one of the most important and massive technology in the polymer manufacturing [2], which is due to the continuity and short time of the process, high mixing efficiency, high capacity, excellent quality of obtained products [3]. Nowadays, intermeshing co-rotating twin-screw extruders are the most common choice for compounding and reactive extrusion [4–6], due to a modular construction, very good mixing capability and good pressure build-up. However, growing demand on the new materials with special and/or high-performance properties enforced the academic and industry to develop novel manufacturing methods based on extrusion technologies [7–9]. In this field of research, the application of multi-screw extruders with unique processing characteristics seems to be very promising approach for future development. However, literature information about application of the multi-screw extruders in polymer manufacturing are still limited. Therefore, this work is aimed to fill the current

[1)] Department of Polymer Technology, Faculty of Chemistry, Gdansk University of Technology, ul. Gabriela Narutowicza 11/12, 80-233 Gdansk, Poland.

[2)] Advanced Materials Center, Gdansk University of Technology, ul. Gabriela Narutowicza 11/12, 80-233 Gdansk, Poland.

[3)] Łukasiewicz Research Network – Institute for Engineering of Polymer Materials and Dyes, ul. Marii Sklodowskiej-Curie 55, 87-100 Torun, Poland.

[4)] Takimsan Disli Kesici Ltd. Sti., Kos-Kop San. Sit. Mısır Sk. No.12, Ömerli Mevkii Hadimköy, 34555 Istanbul, Türkiye.

[*)] Author for correspondence: krzysztof.formela@pg.edu.pl, kformela.ktp@gmail.com

knowledge gaps in this area by comparing features of multi-screw extruders with commonly used twin-screw extruder.

STATE-OF-ART IN THE MUTLI-SCREW EXTRUSION

Fig. 1 shows the general classification of multi-screw extruders, i.e. triple-screw, quad-screw, octa-screw, multi-rotation system (MRS), ring and planetary extruders.

The development of multi-screw extruders for polymer processing is currently at an early stage and, as shown in Table 1, the number of findings on multi-screw extruders in the most popular scientific databases (Google Scholar, Scopus, Web of Science) is still limited.

T a b l e 1. Number of results in different databases depending on the type of extruder

Extruder type	Database*)		
	Google Scholar	Scopus	Web of Science
Triple-screw	91	78	12
Quad-screw	39	18	5
Octa-screw	10	2	2
Multi-rotation system	25	8	0
Ring	52	7	2
Planetary	104	40	6

*) Searching was performed on 05 January 2024

For example, the number of results in the Google Scholar database ranged from 10 (eight-screw extruder) to 104 (planetary extruder), whereas in the Web of Science database the number of results ranged from 0 (multi-screw system) to 12 (triple-screw extruder).

This chapter summarizes the state-of-the-art in multi-screw extrusion based on screw configuration, including the triple-screw, quad-screw, octa-screw, multi-rotation system, ring, and planetary extruder.

Triple-screw extruders

Triple-screw extruders can be divided considering the screws configuration into parallel and triangle-arrayed. Parallel triple-screw extruders are industrially available machines produced mostly in China and Türkiye by company established within last two decades, for example: Useon Technology Limited (2006), Nanjing Kerke Extrusion Equipment Co., Ltd. (2009), Nanjing Cowin Extrusion Machinery Co., Ltd. (2012), Nanjing Kailida Machinery Co., Ltd. (2013) or Polmak Plastik (2009). The main advantages of parallel triple-screw extruders are excellent mixing, self-cleaning, narrow residence time distribution, high torque, and throughput. According to producer's throughput of commercially available parallel triple-screw extruders is in the range: 40–3500 kg/h.

The concept of triangle-arrayed triple-screw extruder was invented and patented by a research group from Beijing University of Chemical Technology in 2001 [10] and commercialized in 2006 [11]. The features in the 2D geometry and flow domain of a co-rotating twin screw extruder and a triangle-arrayed triple-screw extruder are presented in the Fig. 2.

Due to specific construction of a triangle-arrayed triple-screw extruder the extrusion characteristics such as material conveying (flow rate), distributive, and dispersive mixing is much better than for twin-screw extruder [12–14]. Moreover, triangle-arrayed triple-screw extruders can generate good pressure for pumping and conveyance of the processed material, which allow on

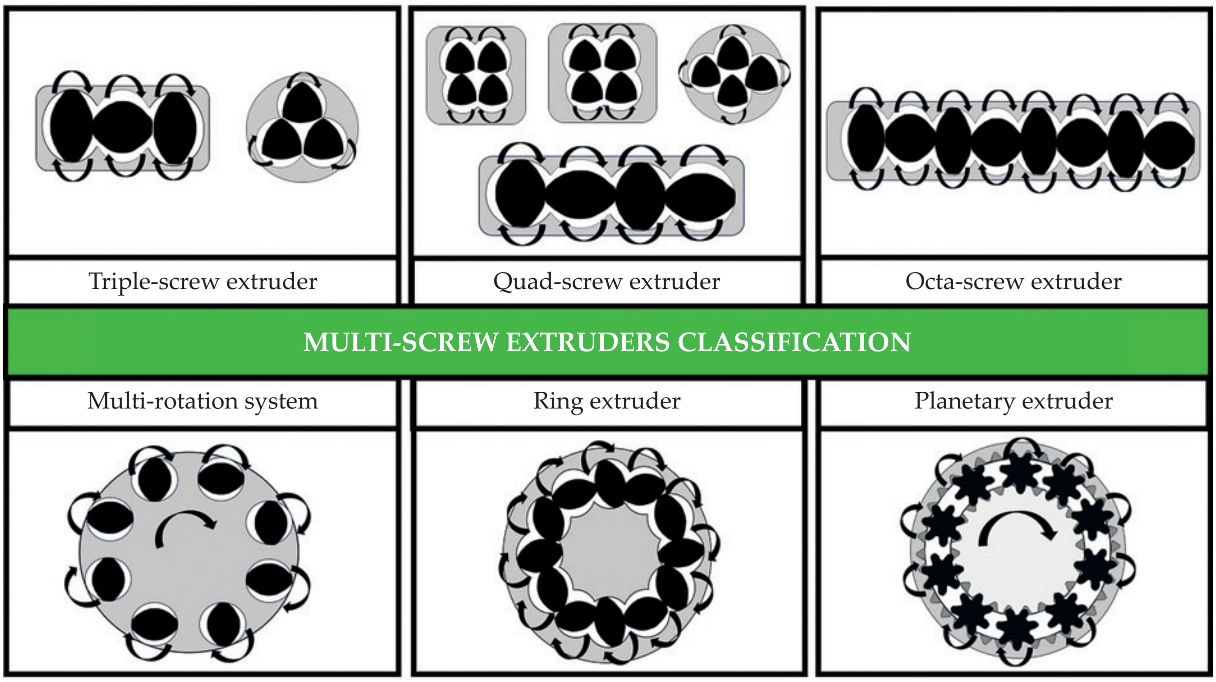

Fig. 1. General classification of multi-screw extruders

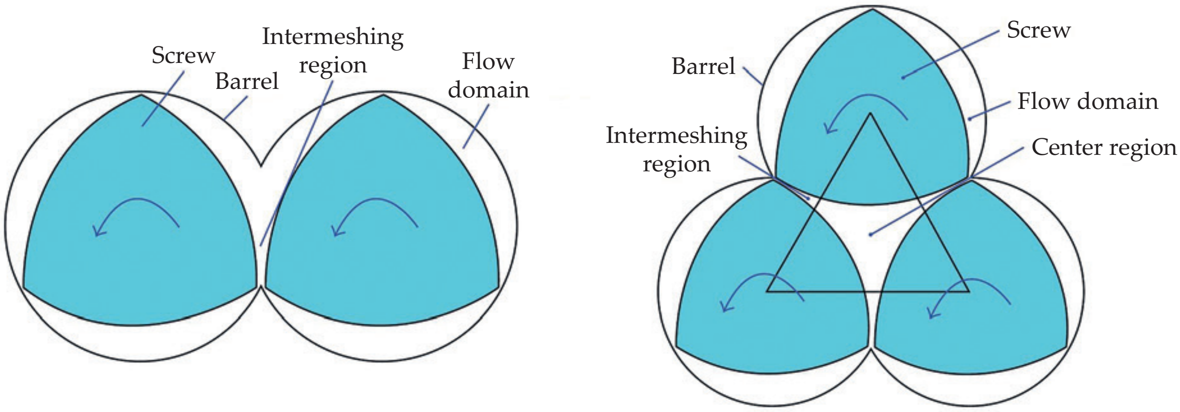

Fig. 2. 2D geometric models of a co-rotating twin screw extruder (left side) and a triangle-arrayed triple-screw extruder (right side) [11]

the manufacturing of high viscosity systems or highly filled masterbatches [15, 16]. According to the literature, power consumption of triangle-arrayed triple-screw extruders is 1.5 times higher than in a co-rotating twin-screw extruder, but at the same time their productivity increase around 1.3 times [17]. Interesting development of triple-screw extrusion technology is its combination with injection molding described in work [18].

Quad-screw extruders

Parallel screw configuration quad-screw extruders are manufactured by the Japanese company Technovel Corporation, founded in 1991. Quad-screw extruders release less self-generated heat from the processed polymers and at the same time lower build-up pressure because degassing of the processed material is much easier [19]. Lower melt temperatures and higher shear in the quad-screw extruder allowed better mixing at higher screw speeds than in the twin-screw extruder [20]. Recently, Alotaibi et al. [21] investigated the degradation of polypropylene recycled by a quad-screw extruder and a twin-screw extruder. The melt flow rate (MFR/MFR_0) and morphology of the tested material were evaluated as a function of the reprocessing cycle and the obtained results are summarized in Fig. 3. It was observed that higher shear forces and longer residence time of the material in the quad-screw extruder resulted in thermomechanical degradation of polypropylene, which was confirmed by rheological and microstructural studies. Similar trends were observed during the processing of polylactic acid [22, 23].

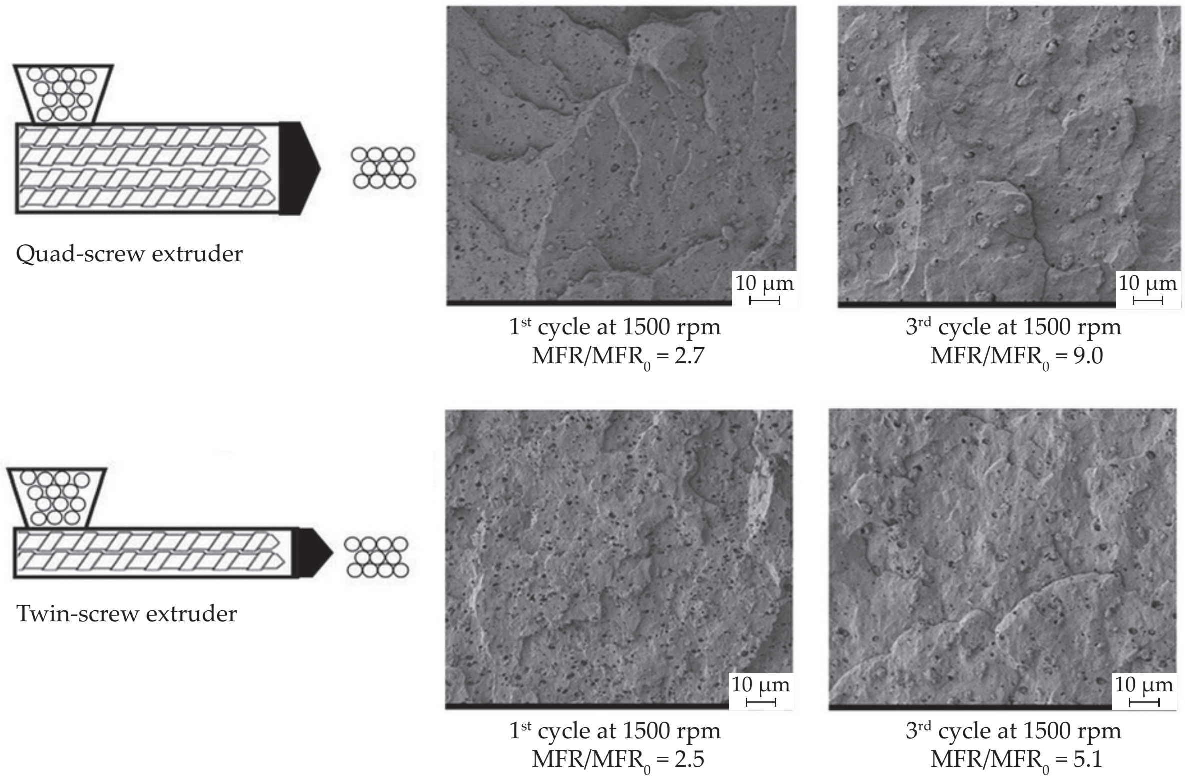

Fig. 3. SEM images and melt flow rate (MFR/MFR_0) of polypropylene reprocessed by quad-screw and twin-screw extruder [21]

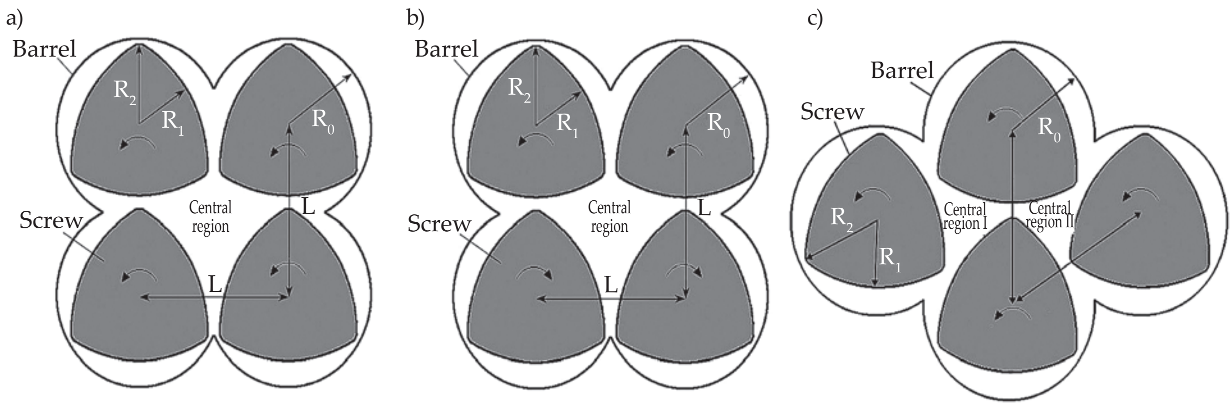

Fig. 4. Cross sections of quad-screw extruders: a) co-rotating square-arranged quad-screw extruder; b) counter-rotating square-arrayed quad-screw extruder; c) equidistance arrayed quad-screw extruder [24]

Furthermore, as presented in Fig. 4, quad-screw extruders can be configured as a counter-rotating square-arrayed quad-screw extruder (Fig. 4a), counter-rotating square-arrayed quad-screw extruder (Fig. 4b), equidistance arrayed quad-screw extruder (Fig. 4c) [24]. Numerical simulation of flow characteristics of counter-rotating square-arrayed quad-screw extruder indicated that power consumption of a counter-rotating square-arrayed quad-screw extruder is 3 times higher than in a co-rotating twin-screw extruder, while their productivity is almost equal [25]. However, these solutions are at prototyping stage.

Octa-screw extruders

The co-rotating parallel octa-screw extruder is a solution manufactured by Technovel Corporation, Japan, which is shown in Fig. 5. As can be seen, the number of screws in the octa-screw extruder is the same as in the ring or planetary extruder, except that the screws are arranged on a flat plane. Recently, Liu et al. [26] studied experimentally and numerically the octa-screw extrusion process, which was compared with the twin-screw extrusion. The obtained results showed that the octa-screw extruder is characterized by a narrower residence time distribution and a lower temperature profile than the twin-screw extruder. The authors indicated that better mixing capabilities with minimized thermal degradation of polymer materials during extrusion are the main advantages of the octa-screw extruders.

Multi-rotation system (MRS)

The multi-rotation system (MRS) extruder was invented in 2007 by the German company Gneuss

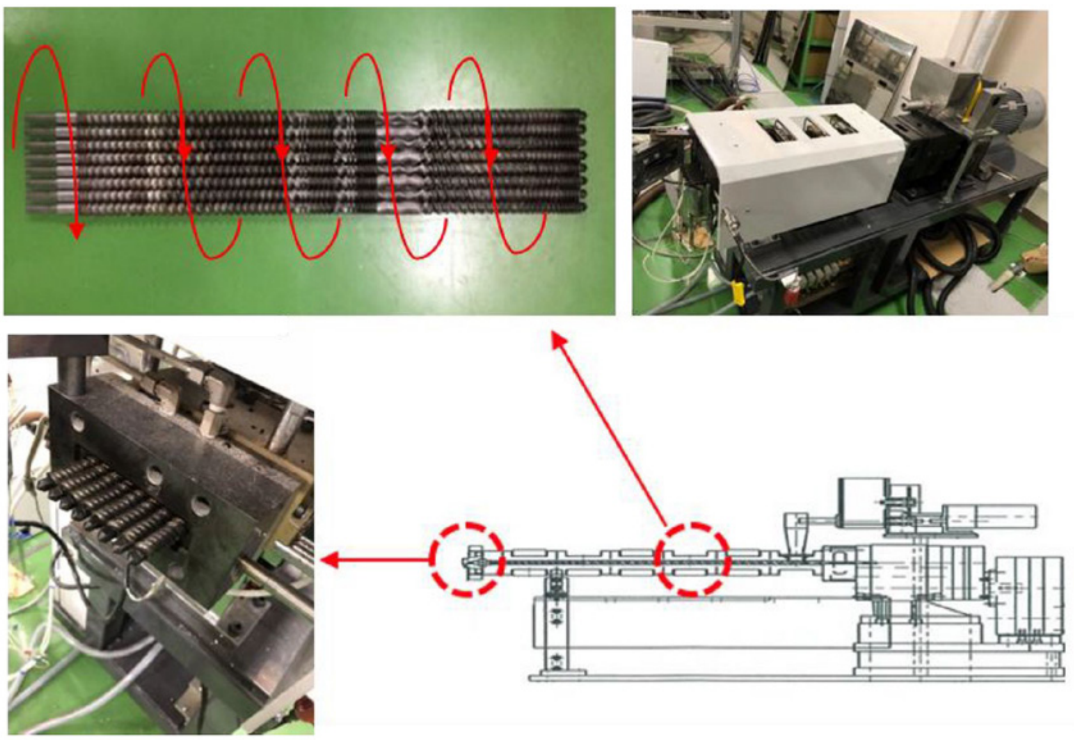

Fig. 5. WDR 8 series octa-screw extruder, Technovel Corporation, Tokyo, Japan [26]

Kunststofftechnik GmbH. The MRS is a single-screw extruder that consists of 8–10 small extruder cylinders, parallel to the main screw axis. These small extruder barrels are "satellite" screws, which are driven by a ring gear in the main barrel. The "satellite" screws rotate in the opposite direction to the main screw and around the screw axis, which significantly increases the surface exchange of the polymer melt. The MRS extruder is characterized by a significantly larger surface area, surface exchange and free volume, and a lower demand for specific energy consumption than a single-screw or twin-screw extruder, which allow for extremely efficient devolatilization or degassing of the polymer melt. In addition, the manufacturer indicates that the MRS extruder offers greater flexibility and less maintenance of dryers and high vacuum systems [27]. The MRS extruder is available with screw diameters from 35 (MRS 35) to 160 mm (MRS 160) or 2×135 mm (MRS 200), allowing production output from 35 kg/h to 2000 kg/h. A comparison of extruder features and energy savings for single screw, twin-screw and multi-rotation extruders (MRS) is shown in Table 2.

T a b l e 2. Comparison of extruder characteristics and energy savings for single-screw, twin-screw and multi-rotation system (MRS) [27]

	Single-screw extruder	Twin-screw extruder	MRS extruder
Parameters (normalized in %)			
Surface, cm^2	100	150	450
Surface exchange, m^2/min	100	200	5000
Free volume	100	150	300
Energy savings (Wh/kg)			
Crystallization	90	–	–
Drying (<50 ppm)	120	–	–
Pre-drying (to 1000 ppm)	–	60	–
Extruder drive and heating	240	230	295
Vacuum	–	90	45
Booster pump	–	30	–
Total (normalized in %)	450 (129)	410 (117)	350 (100)

Ring extruder

Ring extruder was developed in 1998 by Josef A. Blach from Extricom Blach Extruder & Components (currently part of CPM Holdings Inc.) in Germany. Ring extruder consists of at least six co-rotating screw shafts which are arranged in a circle in an extruder housing axis-parallel [28]. Fig. 6 shows the example of screw configuration in ring extruder with twelve co-rotating screw shafts.

In ring extruders transport of processed material takes place in a double helix around the stationary core and around each screw. The gaps between barrel, stationary core and screws co-rotating screw shafts are like gaps found in twin-screw extruders. Such solution allows more frequent passages of the material through the intermeshing sections, which resulting in more efficient mixing and devolatilization comparing to conventional processing methods, such as single- and twin-screw extrusion.

Planetary extruder

The first attempts to use a planetary extruder in polyvinyl chloride processing began in Europe in 1960 at Eickhoff-Kleinewefers Kunststofftechnik from Germany [29]. In a planetary extruder, three elements: the barrel, the central screw (sun screw) and the spindles (satellites) are interlocked due to a 45° toothing. The gap between the planetary spindles (satellites) and the mating surfaces is about ¼ mm [30]. The unique design of the planetary extruder resulted in the material being exposed to large surfaces, which significantly improved mixing, process temperature control (heat exchange) and degassing. The same characteristics are claimed by manufacturers of multi-rotation system and ring extruders, but as shown in Figure 1, their screw configuration is much simpler than that of planetary extruders, which affects the intermeshing sections and the surface area during mixing. However, to the best of our knowledge, there is no published information comparing mixing efficiency of planetary extruder, multi-rotation-system (MRS) and Ring extruder.

Due to complicated construction of screw configuration, the number of planetary extruders producers is limited and includes Battenfeld-Cincinnati Germany GmbH (Germany), Entex Rust & Mitschke GmbH (Germany),

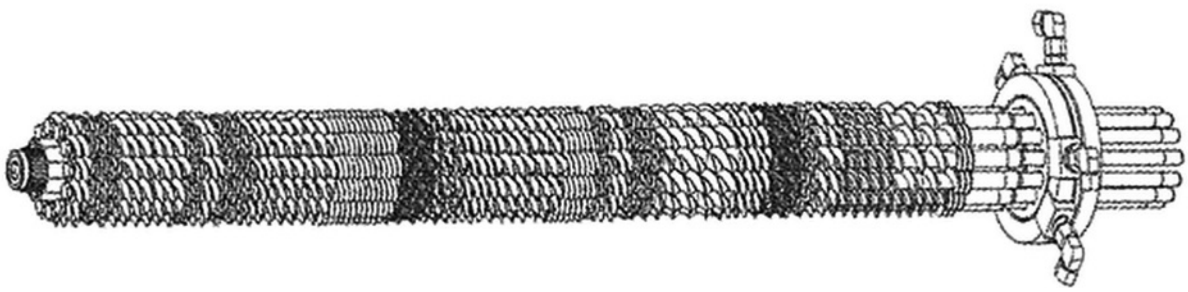

Fig. 6. Ring extruder screw configuration [28]

Beijing Huateng Zhengcheng Industry and Trade Co. Ltd. (China), Yean Horng Machinery C. Ltd. (Taiwan) and Takimsan Disli Kesici Ltd. Sti. (Türkiye). Available on the market planetary extruders size ranging from 30 to 550 mm and throughputs from 0.3 kg/h to 7000 kg/h. However, currently only two companies offer lab-size machine with size below 100 mm: Entex Rust & Mitschke GmbH (Germany) – 30 mm and Takimsan Disli Kesici Ltd. Sti. (Türkiye) – 80 mm. The laboratory planetary extruder PLATEX 80 installed in Gdansk University of Technology is presented in Fig. 7.

In this option, lab-sized planetary extruder can work in two options: as single planetary extruder (one-step extrusion) or can be combined in the cascade with single-screw extruder with granulation system (two-step extrusion). Short, compact, and modular design of planetary extruder allow connection with other extrusion lines, which significantly improves their mixing and/or degassing possibilities. Recent advances in the sustainable development of polymer blends and composites prepared using planetary extruders are summarized in work [31].

LIMITATIONS AND FUTURE DEVELOPMENT OF MULTI-SCREW EXTRUDERS

Over the last ten years, we could observe dynamic development of multi-screw extruders, which were successfully applied for: melt-granulation and pulverization, manufacturing of thermal-sensitive and high-performance materials, high-viscous systems processing, plastics and rubber recycling and reactive extrusion, modification, and/or functionalization of polymers.

Recent developments in advanced production of polymer materials using a multi-screw extruder are summarized in Table 3.

Considering current trends future perspectives for development of multi-screw extruders should be focused on the three main directions:

– development of precise and stable machine parts and units, degassing and feeding solutions, modular construction machines and parts (easy modification and flexibility), high torque extruders.

– lower energy consumption, modeling, optimalization and up-scaling for polymer extrusion processes.

– online/inline process monitoring – real-time process monitoring is crucial for achieving high-quality products and better understanding of processes.

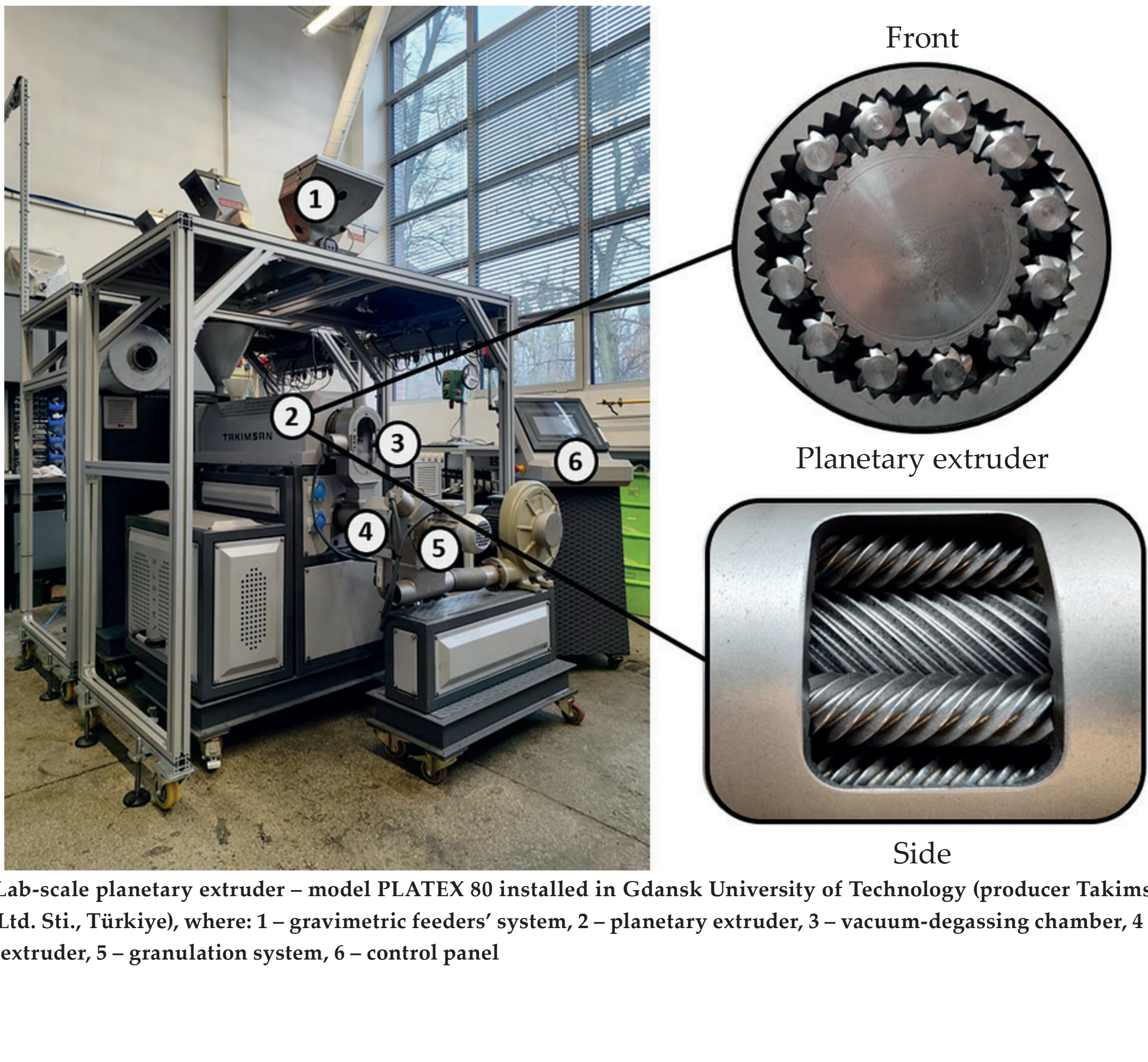

Fig. 7. Lab-scale planetary extruder – model PLATEX 80 installed in Gdansk University of Technology (producer Takimsan Disli Kesici Ltd. Sti., Türkiye), where: 1 – gravimetric feeders' system, 2 – planetary extruder, 3 – vacuum-degassing chamber, 4 – single-screw extruder, 5 – granulation system, 6 – control panel

T a b l e 3. The examples of materials manufactured by different multi-extruders within last 10 years (references published between 2013–2023)

Multi-extruder type	Processed materials	Publication year	References
Triple-screw	polylactic acid/polyethylene glycol porous scaffolds	2013–2015	[32–34]
	polystyrene/polytetrafluoroethylene/poly(propylene carbonate) composite foams	2016	[35]
	microfibrillar polypropylene/polyamide 6,6 composites	2017	[36]
	polypropylene/ethylene propylene diene monomer rubber blends	2018	[37]
	polylactic acid/ nickel-coated multi-walled carbon nanotubes composite foams	2022	[38]
Quad-screw	reactive extrusion of biodegradable polymer blends	2019	[39–41]
	highly filled low density polyethylene/barium strontium titanate composites	2020	[42]
	polypropylene/glass fiber composites	2023	[43]
	polypropylene/multi-walled carbon nanotubes composites	2024	[44]
Octa-screw	polyamide 6/low molecular weight polyethylene blends	2018	[45]
	ultra-high molecular weight polyethylene/graphite composites	2018, 2019	[46, 47]
	ultra-high molecular weight polyethylene/graphene composites	2021	[48]
Multi-rotation system	polycondensates, especially hydrolysable polymers such as poly(ethylene terephthalate)	2021	[49]
Ring extruder	highly filled graphite-polymer composites	2023, 2024	[50, 51]
Planetary extruder	powders for 3D printing	2019	[52]
	wood polymer composites	2019	[53]
	pressure-sensitive adhesives	2020	[54]
	waste rubbers	2021	[55]
	biodegradable materials	2023	[56]
	highly filled rubber masterbatches	2023	[57]
	pharmaceutics	2023	[58, 59]
	used wind turbine blades	2023	[60]

CONCLUSIONS

The application of multi-screw extruders is interesting solution for more complex polymeric systems and/or reactions, thermal sensitive polymers (or additives), specific extrusion conditions or any other processes, where twin-screw extruders are not effective enough to reach quality expected for prepared materials. This mostly due to much shorter residence time in twin-screw extruder compared to the multi-screw extruders.

This work comprehensively summarized current trends in this field of research, which indicated that the processing and production of new polymeric materials using a multi-screw extruder will continue to grow in near future.

Nowadays, the main problem is limited number of research and development units with access to the multi-screw extruders, which resulting in a very low number of published information about their applications. This is obviously related to the high cost of purchase and maintains of plasticizing unit (screws and barrel) in the multi-screw extruders comparing to commonly used single- and twin-screw extruders, which should decrease with increasing number of producers and available solutions.

Limited number of used multi-screw extruders resale on the market indicates that already produced machines are still used which is good sign for future development of this technology. The final decision about used extruder (single-, twin- or multi-screw extrusion) should be made based on the comprehensive analysis of the lab-scale and semi-industrial scale experimental works results, technological and environmental aspects, investment, and maintenance costs.

Authors contribution

K.F. – research concept, methodology, investigation, validation, visualization, writing; A.R. – visualization, writing; A.B. – visualization, writing; B.E. – visualization, writing.

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Conflict of interest

The authors declare no conflict of interest.

REFERENCES

[1] Gomollón-Bel F.: *Chemistry International* **2019**, *41(2)*, 12. https://doi.org/10.1515/ci-2019-0203

[2] Wilczynski K., Nastaj A., Lewandowski A. *et al.*: *Polymers* **2019**, *11(12)*, 2106. https://doi.org/10.3390/polym11122106

[3] Formela K., Zedler Ł., Hejna A. *et al.*: *Express Polymer Letters* **2018**, *12*, 24. https://doi.org/10.3144/expresspolymlett.2018.4

[4] Li T.T., Feng L.F., Gu X.P. *et al.*: *Industrial and Engineering Chemistry Research*. **2021**, *60*, 2791. https://doi.org/10.1021/acs.iecr.0c05078

[5] Leitch J.A., Richardson P., Browne D.L.: *Chimia* **2023**, *77*, 339. https://doi.org/10.2533/chimia.2023.339

[6] Zhuang Y., Saadatkhah N., Morgani M.S. *et al.*: *The Canadian Journal of Chemical Engineering* **2023**, *101*, 59. https://doi.org/10.1002/cjce.24538

[7] Schäfer C., Meyer S.P., Osswald T.A.: *Polymer Engineering and Science* **2018**, *58*, 2264. https://doi.org/10.1002/pen.24847

[8] Justino Netto J.M., Idogava H.T., Frezzatto Santos L.E. *et al.*: *The International Journal of Advanced Manufacturing Technology* **2021**, *115*, 2711. https://doi.org/10.1007/s00170-021-07365-z

[9] Xu M., Liu Y., Ge Y. *et al.*: *The Journal of Supercritical Fluids* **2023**, *199*, 105953. https://doi.org/10.1016/j.supflu.2023.105953

[10] Pat. CN. 2 471 522 Y (2001).

[11] Zhu X.Z., Wang G., He Y.D. *et al.*: *Advances in Mechanical Engineering* **2013**, *5*, 236389. https://doi.org/10.1155/2013/236389

[12] Zhu X.Z., Xie Y.J., Yuan H.Q.: *Polymer-Plastics Technology and Engineering* **2007**, *46*, 401. https://doi.org/10.1080/03602550701242919

[13] Wang G., Zhu X.Z., He Y.D. *et al.*: *Engineering Applications of Computational Fluid Mechanics* **2013**, *7*, 74. https://doi.org/10.1080/19942060.2013.11015455

[14] Zhu X.Z., He Y.D., Wang G.: *International Journal of Rotating Machinery* **2013**, *2013*, 258197. https://doi.org/10.1155/2013/258197

[15] Jiang N., Zhu C.: *Polymer-Plastics Technology and Engineering* **2008**, *47*, 590. https://doi.org/10.1080/03602550802059105

[16] Yang K., Xin C., Yu D.: *Polymer Engineering and Science* **2015**, *55*, 156. https://doi.org/10.1002/pen.23883

[17] Zhu X.Z., Yuan H.Q., Wang W.Q.: *Journal of Materials Processing Technology* **2009**, *209*, 3289. https://doi.org/10.1016/j.jmatprotec.2008.07.045

[18] Xiaochun Y., Youhua Y., Yanhong F. *et al.*: *Advances in Polymer Technology* **2018**, *37*, 3861. https://doi.org/10.1002/adv.22169

[19] Calderón B.A., McCaughey M.S., Thompson C.W. *et al.*: *Industrial and Engineering Chemistry Research* **2019**, *58*, 487. https://doi.org/10.1021/acs.iecr.8b04757

[20] Albareeki M.M., Driscoll S.B., Barry C.F.: *AIP Conference Proceedings* **2019**, *2139*, 020006. https://doi.org/10.1063/1.5121653

[21] Alotaibi M., Aldhafeeri T., Barry C.: *Polymers* **2022**, *14*, 2661. https://doi.org/10.3390/polym14132661

[22] Aldhafeeri T., Alotaibi M., Barry C.F.: Polymers **2022**, *14*, 2790. https://doi.org/10.3390/polym14142790

[23] Aldhafeeri T., Alotaibi M., Barry C.F.: *AIP Conference Proceedings* 2023, *2884*, 090002. https://doi.org/10.1063/5.0168335

[24] Zhu X.Z., Tong Y., Hu Y.X.: *Materials* 2018, *11*, 2272. https://doi.org/10.3390/ma11112272

[25] Zhu X.Z., Xie Y.J., Yuan H.Q.: *Journal of Reinforced Plastics and Composites* 2008, *27*, 321. https://doi.org/10.1177/0731684407084115

[26] Liu C.Y., Mikoshiba S., Kobayashi Y.: *Polymers* 2022, *14*, 1201. https://doi.org/10.3390/polym14061201

[27] Gneuss Kunststofftechnik GmbH.: *Plastics, Additives and Compounding* 2009, *11*, 24. https://doi.org/10.1016/S1464-391X(09)70050-9

[28] *Pat. DE* 102015120586 (2015).

[29] Rauwendaal C.: "Mixing in single screw extruders" in "Mixing in Polymer Processing" (editor Rauwendaal C.) Marcel Dekker, New York 1991, p. 129.

[30] Utracki L.A., Shi GZH.: "Compounding polymer blends" in "Polymer blends handbook" (editor: Utracki L.A.) Springer, Dordrecht 2003, p. 577. https://doi.org/10.1007/0-306-48244-4_9

[31] Formela K., Eyigöz B.: *Express Polymer Letters* **2024**, *18*, 441. https://doi.org/10.3144/expresspolymlett.2024.32

[32] Zhang W., Chen B., Zhao H. *et al.*: *Journal of Applied Polymer Science* **2013**, *130*, 3066. https://doi.org/10.1002/app.39523

[33] Chen B.Y., Wang Y.S., Mi H.Y. *et al.: Journal of Applied Polymer Science* **2014**, *131*, 41181. https://doi.org/10.1002/app.41181

[34] Chen B.Y., Jing X., Mi H.Y. *et al.: Polymer Engineering and Science* **2015**, *55*, 1339. https://doi.org/10.1002/pen.24073

[35] Huang Y., He Y., Ding W. *et al.: RSC Advances* **2017**, *7*, 5030. https://doi.org/10.1039/C6RA26734C

[36] Peng X.F., Li K.C., Mi H.Y. *et al.: RSC Advances* **2016**, *6*, 3176. https://doi.org/10.1039/C5RA19965D

[37] Yang K., Xin C., Yu D. *et al.: Advances in Polymer Technology* **2018**, *37*, 2452. https://doi.org/10.1002/adv.21920

[38] Kuang T., Ju J., Chen F. *et al.: Composites Science and Technology* **2022**, *230*, 109736. https://doi.org/10.1016/j.compscitech.2022.109736

[39] Calderón B.A., Thompson C.W., Barinelli V.L. *et al.: Polymer Engineering and Science* **2019**, *59*, 1986. https://doi.org/10.1002/pen.25197

[40] Calderón B.A., McCaughey M.S., Thompson C.W. *et al.: ACS Applied Polymer Materials* **2019**, *1*, 1410. https://doi.org/10.1021/acsapm.9b00177

[41] Calderón B.A., Soule J., Sobkowicz M.J. *et al.: Journal of Applied Polymer Science* **2019**, *136*, 47553. https://doi.org/10.1002/app.47553

[42] Deshmukh S., Burbine S., Keaney E. *et al.: Polymer Engineering and Science* 2020, *60*, 2782. https://doi.org/10.1002/pen.25509

[43] Aldhafeeri T., Barry C.F.: *et al.: AIP Conference Proceedings* 2023, *2607*, 020007. https://doi.org/10.1063/5.0135878

[44] Kim M.N., Lee H., Cho J. *et al.: Composites Part A: Applied Science and Manufacturing* 2024, *176*, 107827. https://doi.org/10.1016/j.compositesa.2023.107827

[45] Ishigami A., Konno T., Kurose T. *et al.: Academic Journal of Polymer Scienc*e **2018**, *1*, 555563. https://doi.org/10.19080/AJOP.2018.01.555563

[46] Liu C.Y., Ishigami A., Kurose T., Ito H.: "Evaluation of anti-wear properties and internal morphology of graphite filled UHMWPE composites obtained by octa screw extruder process", Materials from first International Conference on 4D Materials and Systems, Yonezawa, Japan August 26–30, 2018, MA2018-03,196. https://doi.org/10.1149/MA2018-03/3/196

[47] Liu C.Y., Ishigami A., Kurose T. *et al.: Journal of Polymer Engineering* **2019**, *39*, 264. https://doi.org/10.1515/polyeng-2018-0288

[48] Liu C.Y., Ishigami A., Kurose T. *et al.: Composites Part B: Engineering* **2021**, *21*, 108810. https://doi.org/10.1016/j.compositesb.2021.108810

[49] *Pat. USA* 20210283814 (2021).

[50] Kiepfer H., Stannek P., Kuypers M. *et al.: Heat Mass Transfer* **2023**; *60*, 785. https://doi.org/10.1007/s00231-023-03398-0

[51] Kiepfer H., Stannek P., Grundler M. *et al.: Applied Thermal Engineering* **2024**, *236*, 121581. https://doi.org/10.1016/j.applthermaleng.2023.121581

[52] Ratecka A.: "Pulverization of highly viscous polymer melts with a planetary roller extruder for selective laser sintering". In: Gamse T, Perva-Uzunalic A, Knez Z. The European Summer School in High Pressure Technology. University of Maribor and Graz University of Technology (ESS-HPT 2019), Graz, Austria; 2019, p. 98. https://doi.org/10.3217/978-3-85125-685-7

[53] *Pat. DE* 112019004180A5 (2019).

[54] *Pat. EP* 3714001 (2020).

[55] Dierkes W., Saiwari S.: "Regeneration and devulcanization" in "Tire waste and recycling", Chapter 7, (editor: Letcher T.M., Shulman V.L., Amirkhanian S.) Accademic Press, Elsevier, Cambridge, Massachusetts, 2021, p. 97. https://doi.org/10.1016/B978-0-12-820685-0.00006-5

[56] *Pat. DE* 102021125395A1 (2023).

[57] *Pat. CN* 116023684 (2023).

[58] Nesges D., Lang T., Birr T. *et al.*: *Powder Technology* **2023**, *427*, 118728. https://doi.org/10.1016/j.powtec.2023.118728

[59] Lang T., Bramböck A., Thommes M. *et al.: Pharmaceutics* **2023**, *15*, 2039. https://doi.org/10.3390/pharmaceutics15082039

[60] Application WO/2023/088951 (2023).

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