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Screw extrusion fused granulate Fabrication: Trends, materials, extruder classification and future development

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A B S T R A C T

This paper presents a systematic review of fused granulate fabrication (FGF), focusing on the classification of FGF extruders, the determination of materials used, and an analysis of past and present trends to forecast future developments. As a rapidly growing field, FGF is increasingly relevant for advancing a circular economy, making it essential to understand the current level of technological achievement from an academic perspective. This review also aims to identify the research hotspots to facilitate future collaborations and classify existing systems to better guide further developments, highlighting gaps in the literature and emerging trends. The review was conducted following the PRISMA guidelines, ensuring a comprehensive and methodologically sound analysis. FGF extruders were classified based on screw length and diameter, identifying small-scale extruders (up to 100 mm in length), medium-scale extruders (100–200 mm), and large-scale extruders (over 200 mm). Additionally, we categorized powder-only extruders, which are typically under 7 mm in diameter, specialized for heat-sensitive materials, and predominantly applied in personalized medicine and scaffold production. Our findings reveal that a wide variety of materials, including high-performance polymers, fibre-reinforced composites, elastomers, and direct regrind materials, are being utilized in FGF. Novel designs, such as in-process material mixing, are also emerging. These findings provide an updated overview of the current state of FGF technology, offering valuable insights for policymakers and research groups. By understanding which class of extruders is suitable for specific applications, stakeholders can make more informed decisions, guiding future research and development in the field.

1. Introduction

Additive Manufacturing (AM) continues to grow rapidly, with techniques making up a substantial part of this industry. Among these polymer-based techniques, material extrusion (MEX) AM is one of the most widely used processes. While Fused Filament Fabrication (FFF) is the dominant MEX method, Fused Granulate Fabrication (FGF) presents notable advantages. By eliminating the need for filament production, FGF expands significantly material choices, lowers energy consumption, and enhances sustainability. It also reduces costs, increases 3D printing speeds, and facilitates easier experimentation with new materials. Furthermore, FGF aligns with circular economy principles, supporting key United Nations sustainability goals [1].

Since the last systematic review of FGF, published in 2021, the field has experienced rapid growth, with the volume of published literature more than doubling. This increase in research output has led to a need for a more recent understanding of current FGF technology. For this reason, an updated literature review that determines both the latest developments as well as changes in research trends, is necessary.

The origin of recent research developments in the field may have a significant correlation with the type of research being conducted. A research group with multiple published articles along the years would highlight a consistent effort towards FGF development. Understanding these aspects along with the geographic distribution of research activity could facilitate future collaborations and enhance knowledge sharing within this research field. In this manner, the development of FGF could be enhanced and accelerated.

One prominent trend in FGF research is the expanding variety of materials used. Although FGF system manufacturers often claim a broad range of compatible materials, users have reported otherwise, particularly when using materials other than standard options like polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS). This issue is particularly pertinent for high-performance thermoplastics, such as polyether ether ketone (PEEK), where FGF systems present a cost-effective alternative to FFF. Similarly, FGF demonstrates superior capabilities in 3D printing elastomers as opposed to FFF and, therefore, it may be interesting to evaluate what was achieved with this improved technology and which materials in general have been used with FGF.

The large variety of thermoplastics and their composites that may be 3D printed using MEX techniques has contributed to the development of a number of FGF screw extruder designs. Previous classifications may no longer adequately capture the nuances of recent innovations, which highlights the importance of a systematic review to provide a more accurate and up-to-date framework.

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This study aims to provide a comprehensive overview of the current state of FGF research by identifying key research groups and geographical regions involved in FGF research, analysing past and recent trends driving the field, examining the subjects and applications covered by studies utilizing FGF, as well as compiling and evaluating the materials and composites applied in FGF systems. Furthermore, this study will classify the types of FGF extruders available, focusing on key dimensions such as screw length and diameter, and identify trends that may indicate future developments. Lastly, it will also highlight new extruder designs that push the boundaries of FGF development and offer new capabilities. In this manner, this review will offer valuable insights for both researchers and industrial stakeholders in the field, contributing to the further advancement and adoption of FGF technology.

2. Methodology

The system review was carried out following the guidelines of the PRISMA process [2]. A pictorial summary of the systematic review process is shown in Fig. 1. The identification of the research articles was carried out on the 7th March of 2024, using the search term shown in Table 1. The term *screw* was placed in the same search term field with *pellet OR granule etc.,* since an article which uses the term *screw* in the context of *additive manufacturing* may still be applicable to the purpose of this literature review. Likewise, an article which mentions *granulates* and *additive manufacturing* but not *screw* is quite common when dealing with studies which make use of FGF technology in a given application. Such articles would fall within this systematic review's scope. For this reason, the *screw* term was included in the same row as the other terms. The exclusion criteria were as follows: review articles, non-English articles, articles older than 2004 which was the date of the oldest article found by previous systematic reviews, and document types which are neither a

Table 1
Search terms used for research article identification.

Field	Operator	Search Term
All fields	AND	"additive manufacturing"
All fields	AND	pellet OR granule OR granulate OR granular OR screw
All fields	AND NOT	metal OR sinter OR sintering OR wire OR arc OR blow OR "powder deposition" OR binder

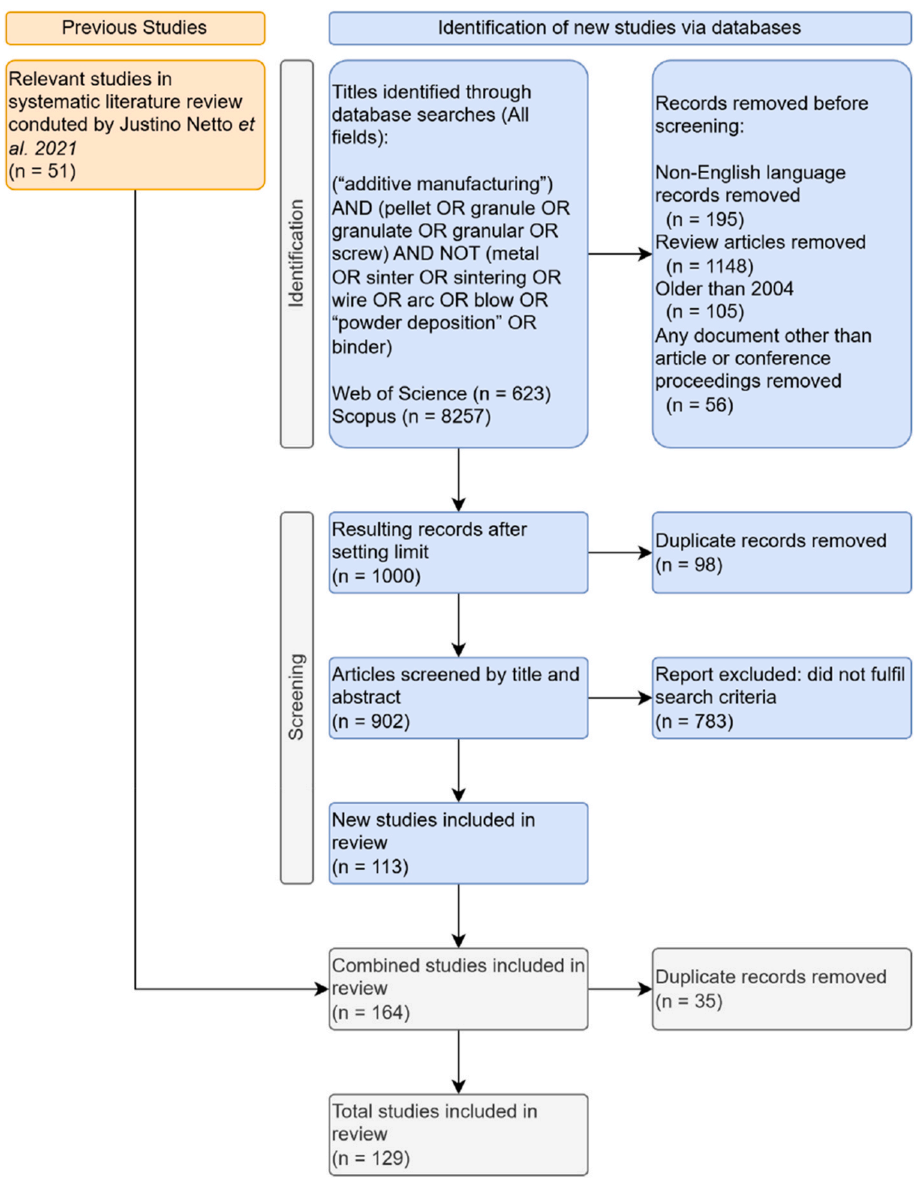

Fig. 1. Flow diagram summary of the PRISMA process adapted for this systematic literature review.

conference paper neither a journal research article. The search terms and exclusion criteria were used with the Web of Science and Scopus databases. The results were 623 and 8257 respectively, which required further filtering before screening. To refine the dataset for effective screening, the first 500 of each database, sorted by relevance, were selected for review. Of these 1000 articles, 98 were found to be duplicates and where removed. The remaining articles were screened by title and abstract and selected based on their relevance with the research aims. This screening process yielded 113 research articles which were then combined with another 51 articles originally reviewed by the Justino Netto et al. [3]. The combined lists had a total of 35 duplicates, which left the final list of 129 unique articles.

Each article was screened to determine the use or otherwise of an FGF system in its methodology. At this stage, those articles which included FGF were screened in more detail to determine, when available, the design of the extruder used. The screw length and diameter as well as the nozzle diameter used in the study, were also tabulated. This data is of an objective nature and therefore does not require multiple reviewers to counter for bias. In certain cases, the screw length and diameter were not provided in the text, but rather as part of figures. In some cases, the figures had a scale and so the data required was collected. In other cases, the text only provided either the diameter or the length of the screw and then supplied an image without scale. In such situations, a scale was created using the information provided, and the necessary data was calculated. Another scenario occurred when research articles used commercially available extrudes to conduct their studies. Often, the length and diameter of the screw were neglected. When possible, the data was collected from the official website and information documents provided by the company supplying the commercial extruder.

Those articles which did not have any information available using the process described, where noted as “N/A” meaning *not available*. For all data metrics collected, any lack of data for that analysis would lead to an omission of the concerned article from the analysis. Extruders for which no information was available regarding screw length and dimensions were not classified using a numerical metric. In order not to neglect these valuable contributions, the studies were classified separately by comparing with similar extruders of known size. This classification process is not deterministic as it does not use a quantified metric and relied primarily on the non-numeric description provided by the authors of the respective studies. Although this approach is not ideal, but given the lack of available information, it was considered the most appropriate option.

Apart from extruder geometry, the materials, composite mix, extruder design and extruder type were tabulated. Extruder design refers to the setup of the physical screw extruder. Most extruders involved variations of the conventional single screw extruder, often altering the screw geometric features such as channel depth, screw length and diameter. These dimensions are shown in Fig. 2. All such extruders were classified as single screw extruders (SSE). In the case of novel or divergent designs, these were classified using the naming scheme provided by the original authors, wherever possible. A distinction was also made to describe whether the extruder was static or was part of the translation motion. Whilst this aspect is not directly related to the extruder design, having a static extruder implies a heavy extruder and therefore was deemed a separate design type. In contrast, extruder type refers to the research group or company used to provide a specific extruder. The extruder type field is concerned with linking studies which used the

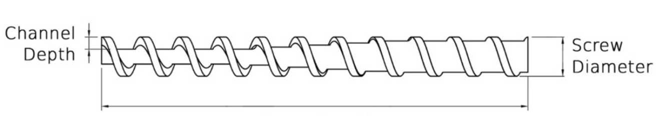

Fig. 2. – Screw length and diameter and channel depth.

same FGF systems. Those studies which used a one-off FGF systems and were custom made by the research group, were marked as “Custom”. In the case of materials and composites, all types of mixtures were recorded except for co-polymerised blends.

The data collected was analysed with the aim of highlighting changes in extruder features with time, classify extruder types and the amount of research conducted on each. The relationship between extruder size, nozzle diameter and how these changed with time, was also evaluated. This analysis should help to generate a comprehensive overview of what studies were conducted on FGF and what is the general path research is taking at this point. The analysis should also highlight any factual extruder design classes present in literature, but that are still undefined up till now. A class here is used to refer to a collection of extruder designs which all share common, prevalent traits. Beyond the extruder design, the materials that were 3D printed up till now were also analysed. The aim of this exercise is to demonstrate which materials have been applied to FGF the most and what are those materials that may merit further attention or that have never been publicly studied with FGF.

Apart from technical data, the data collection process also looked at the author address provided. The aim of this data collection was to understand from which countries are FGF studies originating. Those articles which were produced by researchers from multiple countries were noted. In such cases, each country involved was noted as having a published research article. No preference was given to authorship order. Furthermore relationships between authors and keywords were also evaluated using VOSviewer [4,5]. A co-authorship co-occurrence map was generated, using full counting with 3 minimum documents per author. The same software was also used to evaluate co-occurrence of keywords in the title and abstract of all the articles selected. Binary counting was used with a minimum of 10 occurrences per term. The relevant terms were selected and then generic terms such as “paper”, “lament” and “need” were removed. Spelling differences were corrected, and synonyms terms merged. This form of analysis allowed the determination of principal research groups working in the field of FGF and highlights the main topics being studied.

All of the data collected along with the relevant article details were then tabulated. The table was sorted by publication year and then by alphabetical order and is provided as supplementary material.

3. Trends

Before delving in more detail about the FGF extruders, it is useful to provide a background of where the research is being conducted and which fields are related to it. The location and application of a technology often directs its development and by extension any research conducted.

3.1. Geographic distribution of research

The largest body of published research articles originated from the United States of America (USA), with 25 articles, as shown in Fig. 3. This was followed by China and Spain with 17 and 15 articles respectively. Due to the nature of the European Union (EU) research and related research funding, it is reasonable to combine all EU countries and the United Kingdom (UK) into one group, which would yield the largest research output with 65 articles. This number was corrected to count articles which were published by multiple EU countries and UK as one article. The top countries from this group with the highest article number are Spain, Italy, UK, Germany and then France. India with 15 articles is the fourth most prolific publisher on this subject.

Considering only the extruder found in this literature review, countries with high research output also tend to have locally grown companies supplying FGF extruders. The literature reviewed used extruders from companies listed in Table 2. This does not include those studies which developed their own custom FGF system. Whereas the USA tops both publication and company list, only 2 companies from China have

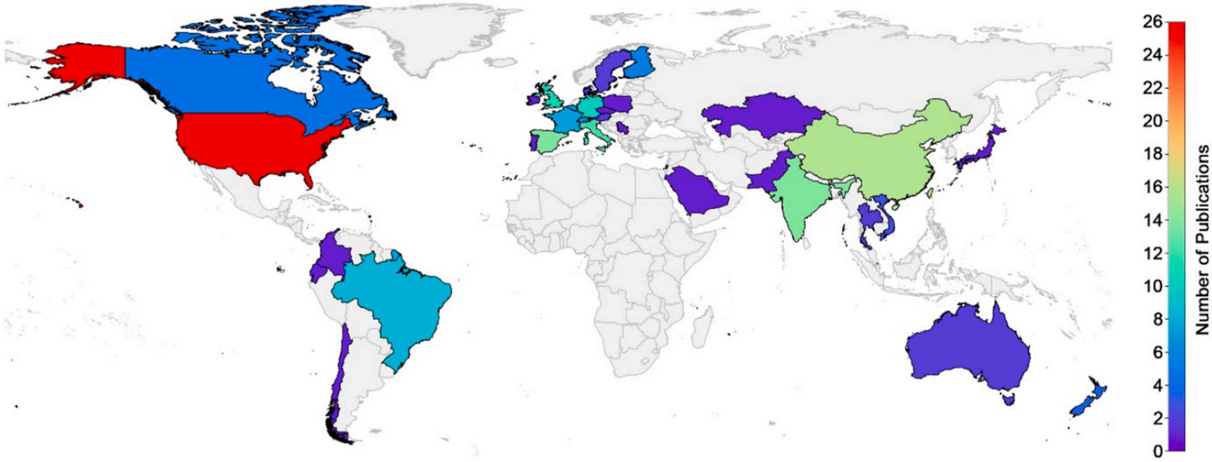

Fig. 3. – Geographic mapping of origin of authors that contributed towards publication of FGF research articles.

Table 2
Companies per country that provide FGF extruders, as mentioned in literature.

Country	No. of Companies	Companies
USA	7	CincinattiMassive DimensionBrinterHybrid Manufacturing TechnologiesStrangpresseCosine Additive3D Cultures
Spain	3	Discovery 3D PrinterMahorIT3D
Italy	3	Wasp 3DDirect 3DCMS
Switzerland	2	RegenHUSAEKI Robotics
Germany	2	AIM3DHerz
People's Republic of China	2	CrealityYizumi
France	1	Pollen AM
United Kingdom	1	FabRx
Colombia	1	Fused Form

been mentioned. Considering that only English-language articles were considered in this review, the results may be biased towards English-speaking countries and overlook significant contributions from non-English-speaking countries such as China.

As shown in Fig. 4, only five research groups have published more than three papers on FGF and have collaborative links with other similar researchers. These groups are geographically spread apart throughout

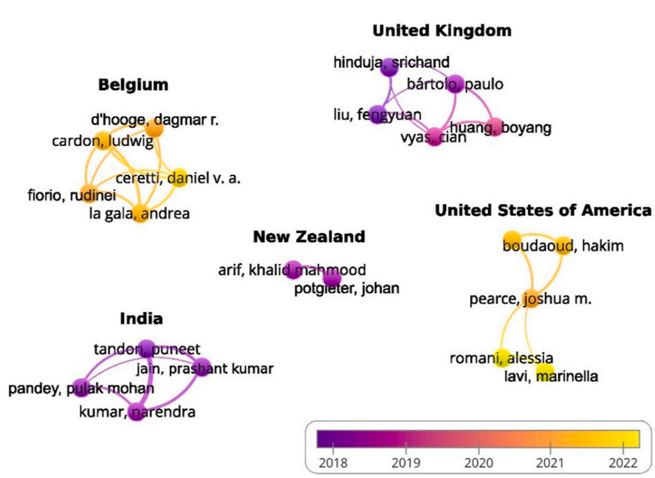

Fig. 4. Co-occurrence web of authorship, colour graded by average publication year. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the world. This result demonstrates how most researchers working in FGF only have a limited exposure to the field before changing subject or shifting completely out of research publication entirely. This aspect is confirmed by the omission of major contributing countries to the FGF research field, from Fig. 4. Studies conducted in China, Spain, Italy, Germany, and France, which were numerous, did not make it in co-occurrence web of authorship, indicating multiple independent studies.

3.2. Overview of FGF research field

The research field of FGF currently focuses on recycling and performance. This statement is demonstrated by the keyword co-occurrence analysis of title and abstract as illustrated in Fig. 5, where both terms are marked in yellow which indicates their prominence in recent literature. The subject of recycling including its aim at a more sustainable future is well linked with FGF's ability to directly use virgin granules or reground waste material in form of regrinds or flakes. Thus, FGF is being perceived as a key technology towards the goal of creating a circular economy. Multiple research efforts have been dedicated to the subject, one such example is the work conducted by Byard et al. with the Gigabot X [6] and similar other studies by the research group of Joshua M. Pearce [6,7], shown in Fig. 4. Other popular terms that surfaced are effect, processes parameter, property, and speed. These terms are linked with efforts to improve the FGF process and the quality of the products manufactured using FGF process. Another separate term of interest is *cost* since FGF is often proposed as a more affordable alternative to filament systems due to the significantly lower price of granules compared to filaments.

The co-occurrence web also highlighted the term strength in yellow indicating the recent interest in this subject. It is generally useless to produce products out of any material from any source if it has inadequate properties and performance. Therefore, it is the driving goal of multiple studies conducted using FGF systems often involved an evaluation of strength. In fact, the term strength often accompanies other terms such as of recycling, performance, composite, feedstock and pellet. All of these terms have a recent, average, publication age which highlights their popularity. Feedstock and pellet are innately linked with FGF and therefore are bound to be prominent. The inclusion of *composite* is indicative of the significant interest towards composite additive manufacturing (AM) even when using FGF. For example, composite materials have been formulated to improve strength via reinforcement, such as done by Hu et al. [8] but also for multiple other objectives, such as controlling the burning process of the material [9]. Such flexibility increases the range of possible applications of FGF.

As indicated by the co-occurrence web, the initial development of FGF was spurned by scaffold fabrication using polycaprolactone (PCL),

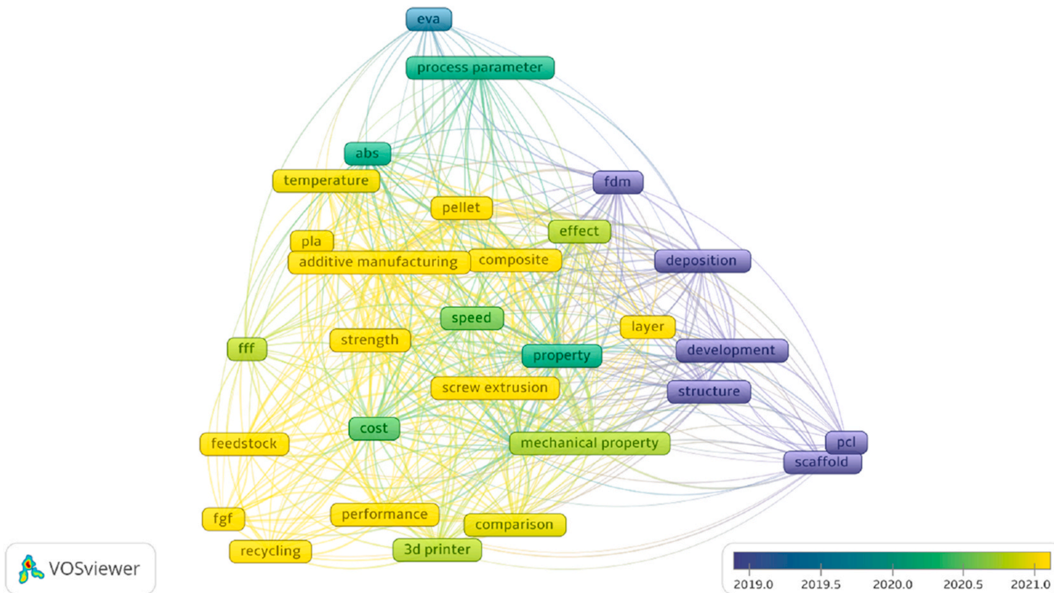

Fig. 5. Co-occurrence web of keywords in the title and abstract, colour graded by average publication year. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

marked in blue in Fig. 5 which indicates its popularity in earlier years. The authorship map, shown in Fig. 4, demonstrate that a significant contribution to this field was provided by the research group of Liu et al. [10–15] as they led the development of plasma treated, screw extrusion fabricated, PCL scaffolds. At the time, the deposition rate and the structure were of interest as these controlled the quality of the scaffolds produced. The low average publication year value of this term indicates that the research interest has shifted away from PCL and scaffolds over the years.

The acronym FDM also lost its popularity with time. This was in part fuelled by the trademarking [16] of the term by Stratasys which led to the counter popularisation of FFF. The term FGF is analogous to FFF and creates a cohesive terminology. It is also notable that other terms such as pellet additive manufacturing (PAM) [17] which are sometimes used to describe FGF systems, were not as widely used as FGF and did not gain enough usages in literature to be present in the web of Fig. 5. Neither FFF or FGF are present in the ISO/ASTM 52900:2021 standard of *Additive manufacturing – General principles – Fundamentals and vocabulary* [18]. Both technologies are grouped under material extrusion (MEX) along with other techniques that are beyond the scope of this review. The lack of popularity of this term is emphasised by its omission in Fig. 5. It is possible that this may change in future publications but the low uptake in MEX term usage since publication of the standard indicates a lack of willingness to adopt this term in the research field. One possible cause may be that the term is too generic as opposed to most studies which tend to be specialized and therefore prefer a more accurate term.

The next development shift was towards additive manufacturing of EVA. A number of research articles were published on auger screw FGF of ethylene-vinyl acetate (EVA) by the research group led by Kumar et al. [19–24]. Fabrication of thermoplastic elastomers is not simple when using a filament fed system. Not only is the quality that FFF can achieve with elastomers inferior to that using rigid thermoplastics but the level of softness useable with FFF is often limited to around 70 shore A [25]. At lower shore hardness, the filament feeding system tends to buckle the filament, leading to incorrect extrusion. This issue does not exist within FGF, and therefore, the first research works using FGF systems focused on elastomers.

Regarding materials, the first thermoplastic to be extruded using FGF was PCL, followed by ABS, and then PLA. The latter two are cornerstones of thermoplastic material extrusion (MEX) AM. The flexibility of FGF lends itself well to the study of highly specialized and experimental materials. In contrast with FFF, FGF eliminates the need for filament production, a step with its own challenges leading to a poor-quality filament and inconsistent extrusion. This simplifies the whole AM process, which allows for studies focusing mainly on material properties and applications. Although FGF has been used to study a diverse range of materials, this cannot be seen in Fig. 5 since many of these studies are one-off experiments. While the mainstream AM thermoplastics such as PLA and ABS have been more extensively investigated, only a few non-mainstream thermoplastics such as EVA and polypropylene (PP) have been explored in multiple studies.

4. Materials used in screw extrusion FGF

Fig. 6 shows all of the materials along with any mixtures thereof that were used in the literature and reviewed in this study. The most used thermoplastic was PLA, followed by ABS, both of which are widely used in FFF systems. Notably polyethylene terephthalate glycol (PETG) is not as widely applied in FGF studies as in FFF. In total, 53 different matrix materials have been studied whilst using FGF. Most research involved 3D printed composites, with the most tested fillers being carbon fibre and glass fibre. Wood and cellulose fibre have also been tested as fillers for multiple thermoplastics due to their desirable properties and aesthetic [26–29].

Flame retardant additive [9], graphene [30–32], bioglass [33] and titanium nano powder [34] have also been used with multiple thermoplastics. Graphene and bioglass were utilized in order to improve cell viability and proliferation in biomedical scaffolds [30,33]. The addition of graphene nanoplatelets was also found to improve mechanical properties [35], where graphene oxide nanosheets allowed the compatibilization of PLA/PBAT blends [32]. The addition of titanium dioxide nanoparticle to recycled PLA was found to improve thermal stability and degree of crystallinity along with tensile strength. In this manner the loss in mechanical and thermal properties brought about by remelting of PLA were counteracted by the nano powder addition [34]. Apart from the fillers and additives just mentioned, another 23 have been used in conjunction with only one other base thermoplastic. The necessity to 3D print so many different materials led to the development of numerous extruder designs, some of which specifically intended for inline mixing

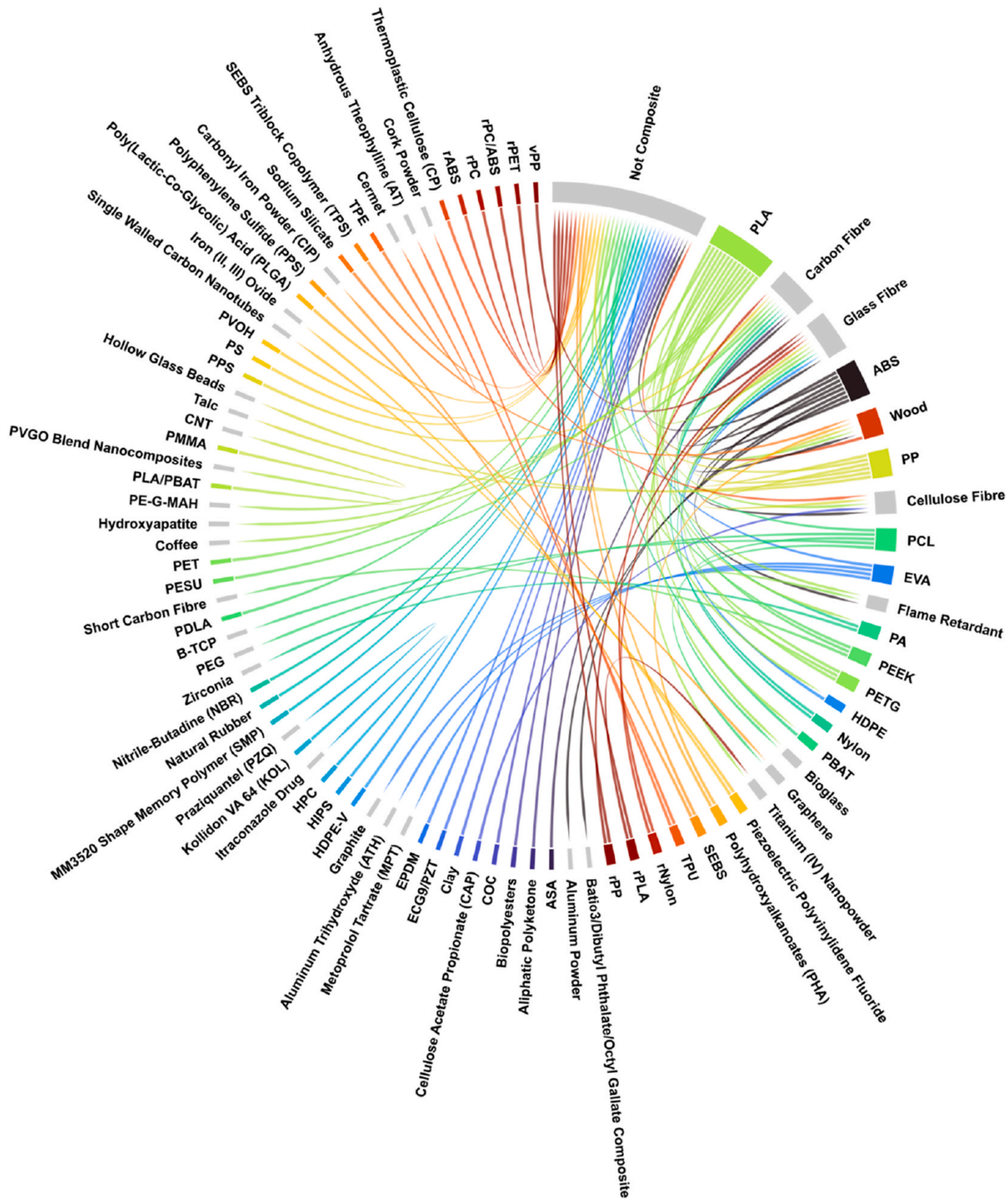

Fig. 6. Chord diagram ordered clockwise by count showing material to fillers and additive links.

of composites [36] and others meant to be used with continuous fibres [37].

5. FGF extruder classification

The number of published articles that either makes use off or develop FGF systems for MEX has been increasing yearly. Last year i.e., 2023 was the most prolific as shown in Fig. 7. Out of the 129 research articles selected, 71 used custom developed FGF systems. Multiple designs exist, some intended for specific applications or materials.

5.1. Screw design

The most popular configuration and the one which will be considered first, is the simple single screw extruder. This design has been popular since the very beginning and most other designs can be considered as variations from the original concept. The most significant variation was to use of a Moineau pump [38] and the application of a flexible heated hose [39]. An advancement over the single screw extruder is the twin screw extruder [40] as well as the application of multiple screws in the same extruder. In the former case, twin screw extruders are meant to provide improved, inline material mixing possibly with a direct control of the component mix during the 3D printing process [40]. Double stage screw extruders employ a different approach for the same result. Two screws feed material by solid conveying to a primary extrusion screw which then plasticates and extrudes the mixed, composite [36]. Such study represents the current edge when it comes to 3D printing of functionally graded composites using FGF. Another interesting advancement is the use of FGF for interfacial impregnation of fibre tows, enabling continuous fibre reinforcement in 3D printed parts [37].

Concerning the variation of single screw extruders that have been found in the literature review, the basic process remains the same in all cases. No compression screws can be deemed the simplest type of screw

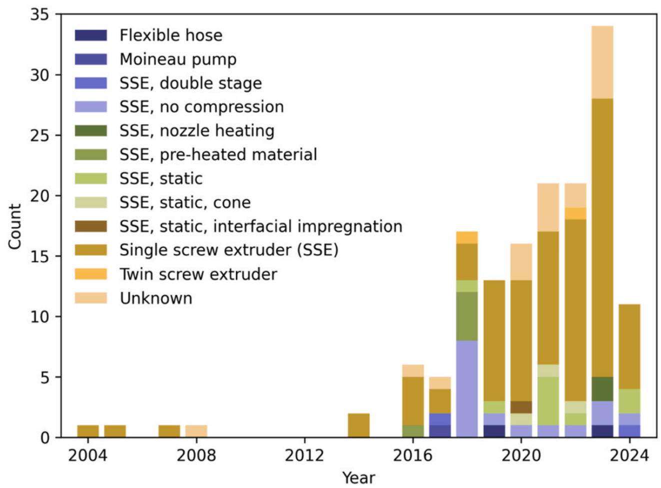

Fig. 7. Histogram of published research articles based on extruder type used.

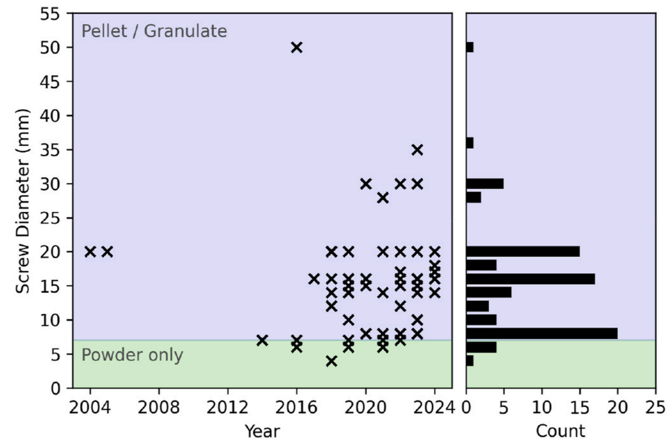

Fig. 8. Screw diameter vs research article publication year with histogram of screw diameters.

extruder, often suffer from poor 3D printing quality when used with rigid materials [41,42]. Other studies utilized classic compression screws but focused on the heating methodology, using nozzle heating. As demonstrated by Curmi et al., in small scale FGF, conduction heating is the primary source of material heating in FGF as opposed to viscous heating which dominates larger extruders [43]. Other studies tried to further miniaturise the extrusion system by using conical extruders which decreased in diameter [44]. Lastly, large and especially medium scale extruder tended to be heavier to move using small motion systems and instead the build plate was moved whilst the extruder remained static. The extruder itself would be similar to other single screw extruders. Given the large number of single screw extruder studies, it may be useful to determine a metric to classify the different extruders, as done in the following section.

5.2. Screw diameter

The classic single screw extruder has multiple parameters that can be varied to produce a different system. The two most important parameters are the screw diameter and screw length. The diameter can be used to classify what kind of material can be fed. Most thermoplastic granulates or pellets have the smallest dimension of around 3 mm which means that the screw feeding channel depth has to be the same or higher than this value. Screw channel depth is rarely provided in literature and therefore cannot be used as a classifier. Comparing the studies that used small diameter screws, the smallest diameter system that managed to properly extrude using pellet feedstock was the V4 commercial extruder by Mahor, which has an 8 mm diameter screw [45]. A version of the Mahor extruder is also used in FGF systems by Tumaker [46]. The next smaller diameter system used a powder feedstock with a screw diameter of 7 mm, developed by Silveira et al. [47]. Larger diameter screws can progressively make use of larger pellets or granulates. Using these observations, the screw diameter classification was divided into two classes: *powder extruders* (Ø $\leq$ 7 mm) and *pellet or granulate extruders* (Ø $>$ 7 mm), as plotted in Fig. 8.

There are significant differences between powders and pellet feedstock. Powder feedstock is usually more expensive than classic pellets from which it is generally produced. The production process to create powder also requires equipment as well as energy and labour, reducing the overall sustainability of the FGF process. Availability is another key factor. Pellets are easily accessible due to their widespread use in mass production and industrial processes, making them easier to source and offering greater material versatility. These aspects could contribute to the relatively low amount of published literature on powder extruders as compared with pellet/granulate extruders.

Compared to powder extruders, pellet extruders offer a much wider spectrum, with a range of tested screw diameters. As the histogram shows, most extruders used in the reviewed literature had a diameter of 8, 16 or 20 mm. Only a small number of systems used different screw diameters. A screw diameter of 8 mm is a natural size limit due to the typical dimensions of pellets. A smaller screw diameter would require an even smaller screw root, which could impair the screw's torsional strength. Increasing the screw diameter to 16 mm makes it large enough to sustain easier granulate feeding and to generate a higher torque. At this diameter the channel depth can reach 6 mm with a screw root of 4 mm diameter. Increasing further the screw diameter to 20 mm allows for a thicker screw root diameter leading to higher sustainable torques which can be used to extrude a higher sustainable throughput [48]. The 16 mm and 20 mm diameter are also widely used in large, stationary, industrial extrusion and injection molding processes, making them easier to procure and adapt to FGF. Furthermore, most of the screw extrusion theory available has been developed using extruders of this diameter [49]. Therefore, it is simpler to study the phenomena occurring during FGF processing when using a system with such a screw diameter. Increasing the screw diameter further than 20 mm is rather rare. All the studies that used such extruders made use of composite feedstock. These large systems are usually more adept at handling a higher percentage of reinforcement without clogging. They can also sustain the extra resistance caused by the increase viscosity of the thermoplastic melt with reinforcing fibres. The two main companies that provide extruders of these sizes and that were found in the literature review are Cincinatti (USA) [50–53] and Massive Dimension (USA) [54,55].

5.3. Screw length

The overall size of an extruder is best characterised by the screw length. In practice, weight is the most important specification of an extruder but often this is hard to come by, especially for custom made systems. As noted earlier, custom systems make up nearly 55 % of all extruders found in the review. However, none of these provided the weight of the extruder. For this reason, the screw length was deemed the most reasonable parameter to classify the bulkiness or size of the extruders. Only a small number of commercial systems reported the extruder weight, making screw length a more reliable metric for a comprehensive review of the literature due to the greater availability of data. The screw length (l) classification was divided into three classes: small ($l \leq 100$ mm), medium ($100 < l \leq 200$ mm) and large ($l > 200$ mm), as plotted in Fig. 9.

The small extruder classification is based on the idea that if the screw length is smaller than or equal to 100 mm, it may be used in desktop 3D printing systems. Such systems are the most widely used in FFF 3D

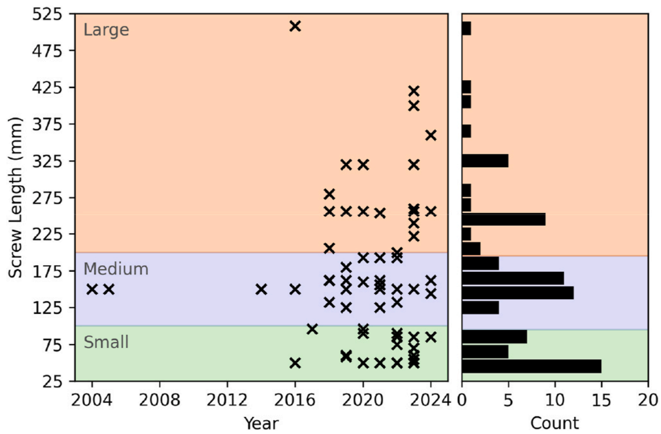

Fig. 9. Screw length vs research article publication year with histogram of screw lengths.

printing that have dominated the domestic market. These small sized 3D printing systems are also amongst the first forms of 3D printers that users tend to purchase when they are still learning about 3D printing. Popular examples are the Prusa MK4 3D printer [56] and Bambu Lab 3D printers [57]. Therefore, the small type FGF extruders are critical drivers towards a wider adoption of FGF in commercial, industrial and domestic sectors. The histogram in Fig. 9 also shows a clear distinction in extruder screw lengths dividing the small and medium categories. This suggests a common design intent amongst various research groups and companies. The first published study using a small extruder appeared in 2016, after which its popularity began to rise [58].

The earliest FGF extruders were developed using medium-sized extruders. At this scale, the motion system can remain similar to that of smaller extruders, with some modifications to handle the increased weight. At the longer length limit of medium scale extruders, the size increase becomes significant enough to warrant a major redesign of the motion system. Such extruders are at the edge between medium and large classifications. Unlike with small extruders, the further increase in the extruder size diminishes the possibility and therefore the need for integration with existing motion systems. In fact, the distinction between medium and large extruders, as shown in the histogram of Fig. 9, is less pronounced than the division between small and medium ones. The medium class is arguably the most adaptable, making it an ideal test bed for advancing FGF technology. At this scale, engineering designs are easier to produce, as they avoid the challenges of miniaturization faced by small-class extruders and the heavy load requirements and material handling typical of large-class extruders. From a technical standpoint, medium FGF systems can still be relatively simple, making them cost-effective and accessible compared with large scale FGF.

Aside from size, the main differentiator between medium and large extruders is what they can produce. Large systems, often referred to as big area additive manufacturing (BAAM) have an application profile that includes large products such as life-size furniture and boats amongst others [59]. Producing such items with small or medium-sized FGF extruders would be highly challenging, and even if it is possible, the production time would be prohibitively long. In essence medium class extruders are more akin to small extruders with greater throughput capacity, feedstock morphology variety and are generally more robust, albeit with an increase in weight. In contrast, large extruders stand out as a class of their own, requiring different process considerations and offering capabilities beyond those of their smaller counterparts.

5.4. Nozzle size

Another differentiator of MEX 3D printing processes is the nozzle size. The smaller the nozzle size, the smaller the parts that can be reasonably produced. From a MEX perspective, the smaller the nozzle, the greater the resistance to flow and therefore the smaller the maximum throughput The effect of nozzle size on the FGF process as well as on the 3D printed parts themselves, makes it an important process parameter. For this reason, the nozzle sizes found in the literature review are plotted against screw diameter and length, with colour grading for publication year, as shown in Fig. 10.

As shown in the plot, there is a trend of larger extruders using larger nozzle sizes. Nonetheless, small style extruders sometimes also made use of large nozzle sizes, e.g. when extruding clay as done by Pitayachaval et al. [60] and when using composite ABS with glass fibres by Liu et al. [61]. The reverse is also true as exemplified by the work of Romani et al. when 3D printing using recycled polycarbonate (rPC) and rPC/ABS blends with a 0.8 mm nozzle on the Gigabot X [7] and by Mi et al. when testing a novel application of a sheering feature in the form of a blister ring, at the metering section [62]. These incongruencies demonstrate that the use of the nozzle size is flexible amongst FGF classes.

Screw length and diameter can be used separately as these parameters are independent of each other, as can be seen in Fig. 10. By convention, most industrial extruders, not meant for additive manufacturing, make use of a 20:1 or 30:1 length to diameter (L:D) ratios. This is often not the case in FGF as can be seen in Fig. 10. Most extruders feature an L:D ratio of 20:1 or lower, with only a small number exceeding this ratio. As the L:D ratio increases, the screw lengthens, resulting in a longer, heavier, and more cumbersome extruder. Consequently, this increase in size adds complexity and cost to the required motion system. A number of extruders opted for L:D ratios smaller than 20:1. This design decision was necessary to miniaturise FGF systems as much as possible and in so doing decrease the complexity and cost of the related motion system. The reviewed research articles reveals that 44 out of the 75 known L:D ratios (58.7 %) fall within the range of 10:1 or smaller. This indicates that the conventional design guidelines used for static, classic, shop floor-type screw extruders are not applicable to MEX AM, despite both being a form of screw extrusion process. The distribution of publication year also shows a trend towards smaller extruder with a smaller L:D ratios and larger extruders with an L:D ratio not more than 20:1. Nevertheless, the interest towards powder extruders seems to have decreased, with recent publications focusing more on granulate extruders. This was probably caused by the smaller application spectrum of such systems.

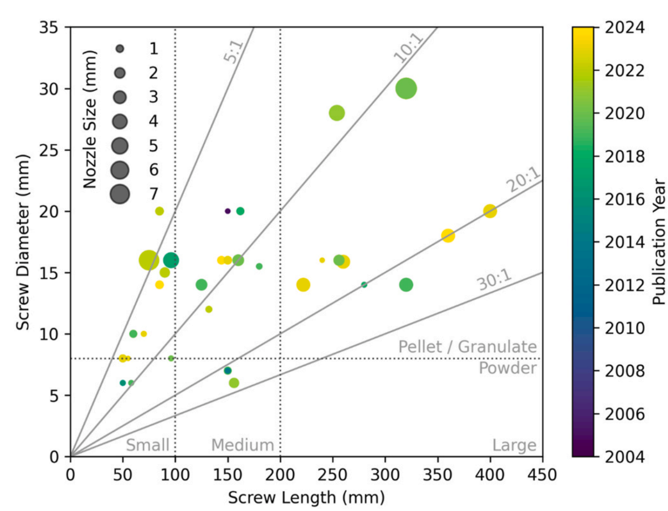

Fig. 10. Extrusion screw diameter vs length, with nozzle size and publication year. Grey line denotes the L:D ratios of studies in that region. Dotted line demarcates the classes based on screw length and diameter.

6. FGF extruder studies

The following section is meant to briefly outline the major findings of the studies being reviewed. The classification system presented in the previous sections has been used to structure this section.

6.1. Powder extruders

Powder-only extruders have been successfully developed for specialized applications, particularly in the biomedical field. Initial studies conducted by Tian et al. [26], Boyle et al. [41], Samiul et al. [42] and Drotman et al. [58] developed four distinct powder extruder systems. These studies concluded that a compression section is necessary in screw extruders to allow for consistent extrusion [41,42], while a fast screw compression ratio results in a decreased extrusion rate [26,27].

Powder-only extruders, particularly the M3DIMAKER 3D printer from FABRX [63], have emerged as valuable tools for biomedical applications, especially in scaffold production for cell growth and personalized medicine. This system allows direct 3D printing of multi-component blends, as demonstrated by Aguilar-de-Leyva's et al. [64] that worked on thermoplastic polyurethane (TPU) tablets blended with theophylline drug and as a ternary blend with magnesium stearate. Silveira et al.'s pioneering research in 2013 laid the groundwork for using powder-only extrusion in scaffold production, focusing on PCL-based materials such as PCL [47,65], PCL/b-TCP [66], and PCL with Bioglass [33]. This early-stage research employed a near 20:1, L:D ratio screw with a single heated zone [67]. Both pre-compounded and dry mixed PCL with bioglass were used but extrusion quality of the latter was inferior. This is an indicator that in such cases a mixing section may be necessary [48].

For thermoplastics with a low melting point, Phung et al. [68] and Nguyen et al. [69] suggested the use of a PTFE extrusion screw as opposed to a conventional metal screw. The PTFE screw required a larger screw root diameter whilst using a shallow channel depth. The latter decreases the molten material residence time, which potentially decreases the degradation of heat sensitive materials. This aspect was studied further by Zhou et al. [70] which used a 1.5 mm deep screw channel and multiple feeding ports along its length, as shown in Fig. 11 (a). As needed, this feature can effectively decrease the working screw length, thereby decreasing material residency time.

Mixing components in a controlled manner during the 3D printing process can be particularly advantageous as it allows for the creation of components with functional gradients. This was the objective of the twin screw extruder developed by Justino Netto et al. [40,71], shown in Fig. 11(b and c). Further research is required to fully develop this technology, but its successful implementation could extend the applications of powder screw extruders beyond the biomedical field.

6.2. Small scale

Extruders with a screw length of 100 mm or less, excluding powder extruder, were classified as small-scale extruders, totalling 21 separate studies. Out of the studies, 6 used in-house developed extruders, while 2 utilized commercial extruders [45,46].

The Mahor extruder is the most widely used commercial small-scale FGF extruder [45]. A modified version of this extruder is implemented in the Tumaker (IT3D) 3D printers [46]. It employs an 8 mm diameter and 50 mm long screw, resulting in an L:D ratio of 6.25:1. This extruder, positioned at the bottom left corner of Fig. 10, is capable of 3D printing complex geometries [72] and can be used with minimal modifications on existing FFF motion systems [73]. It was employed by multiple research groups for 3D printing of elastomers such as vulcanised rubber [74], TPU with cork powder [75] and EVA blended with a medical compound [76]. The Tumaker 3D printer was similarly applied by Georgopoulou et al. [25,77] for 3D printing of unfilled styrene-ethylene-butylene-styrene (SEBS) grades of 25, 50 and 75 shore A even with the addition of 50 % carbon black filler. These materials were then applied to 3D print inflatable actuators and soft compliant robotic grippers. Extrusion and 3D printing of composite materials performed best when using pre-blended feedstock. This is a common shortfall of small scale FGF caused by the short screw being used which was not capable of distributing and dispersing the composite material. Nevertheless, this aspect should not understate the capability of the Mahor FGF extruder to 3D print using thermoplastics of various viscosities, to a greater extent than FFF systems [76].

The Mahor extruder was found to be able to directly extrude reground PLA whilst achieving similar mechanical properties to virgin PLA [78,79]. However, it was reported that the reground PLA was more difficult to extrude and prone to clogging, even when the feeding section temperature was decreased. On the other hand, 3D printing using recycled PLA with FGF decreases material degradation compared to FFF [79]. This was attribute to the extra thermal cycling necessary to produce the filament for FFF [79]. On another occasion, the study by Pagés-Llobet et al. [80] using a Tumaker FGF system concluded that FGF 3D printed parts had improved mechanical properties over FFF. This went against previous studies [78,79], which is most probably caused by

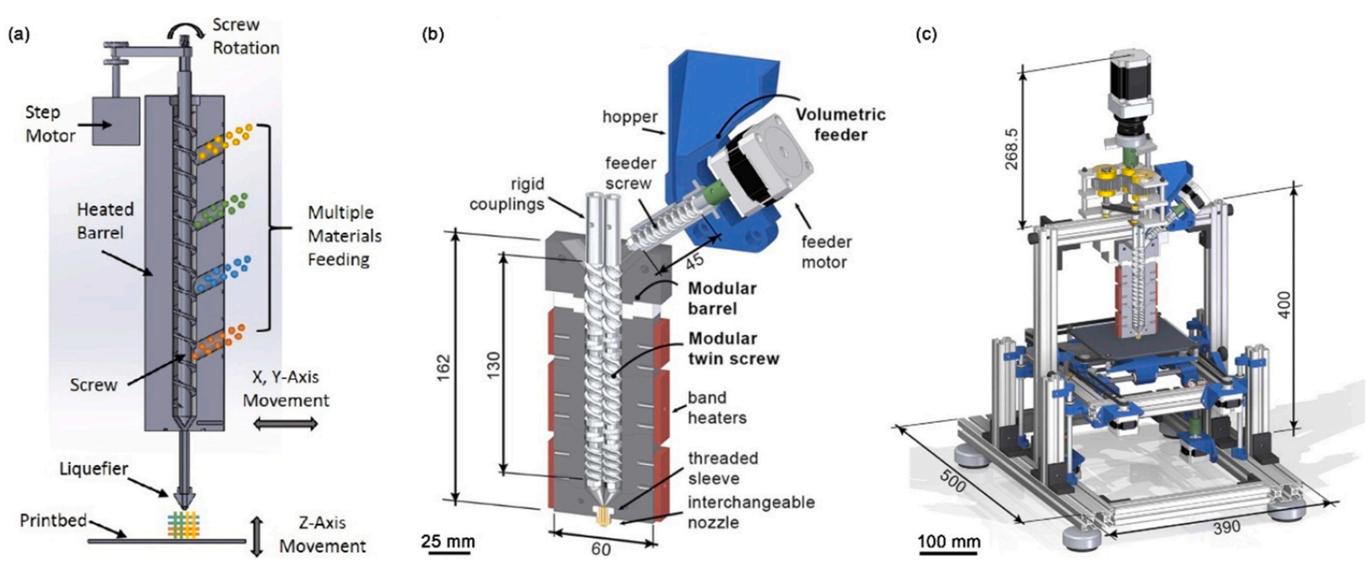

Fig. 11. Schematic of multiple feeding port extruder (a), co-rotating twin screw extrusion head (b), and twin screw 3D printer (c) adopted from Refs. [40,70].

the unusually low density of the FFF parts which indicates abnormal printing conditions.

The Tumaker 3D printer was also successfully employed for 3D printing of biopolymer thermoplastic including heat sensitive material such as polyhydroxyalkanoates (PHA) [81]. The research group led by Martinez also successfully 3D printed PLA pre-blended with micro-fibrillated BioPA to improve fracture toughness and strain at failure [82]. These kinds of studies demonstrate the material extrusion versatility of small-scale FGF extruders which allows the technology to be applied to various fields, ranging from consumer, automation, and even to biomedical.

The quality of small-scale FGF achievable today can be partly attributed to the pioneering studies by Whyman et al. [83,84] back in 2018 which were then applied further by Harris et al. [85]. The initial extruder designs used aluminium barrels which suffered from rapid wear which contaminated the extrudate. Nonetheless the system was capable of 3D printing complex geometries, despite issues with clogging caused by the aluminium wear particles. In contrast, the small-scale FGF extruder developed by the research team of Liu et al. [37] could 3D print polyamide (PA12) with continuous carbon fibre reinforcement through co-deposition, as shown in Fig. 12. In this investigation, screw extrusion was employed to generate the requisite pressure which was essential for achieving near complete impregnation of the 1 K carbon fibre tows, resulting in a porosity level of 0.15 %. Such systems allow the fabrication of load bearing components for specialized applications.

Finally, the first small-scale FGF system capable of 3D printing PEEK was developed by Curmi and Rochman [43,86]. The study demonstrated that PEEK can be extruded and 3D printed using an extrusion screw with a low L:D ratio of 4.25:1. The tensile strength achieved with PEEK was below that of injection molded specimens, which was however attributed to the lack of heated chamber [86].

In conclusion, small-scale FGF extruders have shown capabilities comparable to those of FFF for all thermoplastics groups including high performance polymers. The success of these extruders is now prompting studies into 3D printing of high-performance composites. Research on small-scale FGF has also highlighted its potential for elastomer 3D printing. Further investigations are required to enhance the capabilities in this domain and to explore novel applications of this technology.

6.3. Medium scale

The medium class includes 32 individual studies and all of which utilized custom-developed extruders. These extruders feature screw lengths longer than 100 mm but no more than 200 mm, excluding powder extruders.

The first published journal article on FGF was a medium class extruder which pioneered PCL scaffold fabrication using FGF. It was published in 2004 by Wang et al. [87] using a system developed by Anna Bellini in 2002 [88]. This system utilized a custom screw with a compression and metering section, unlike the later studies published by Kumar et al. which employed an auger screw extruder setup [19–24, 89–92]. This compression less system worked adequately when using elastomers, namely EVA [21,23,24] even when blended with additives such as graphite powder [20,90]. On the other hand, rigid polymer failed to extrude consistently, indicating that such polymers may require a compression and metering section in the extrusion screw for consistent extrusion [91–93].

Apart from elastomers, custom FGF extruders were also employed for testing of biopolymers including PLA and PBAT [94,95] as well novel applications of conventional thermoplastics, such as PP [96]. Two of the biggest barriers to 3D printability using MEX processes are shrinkage and poor self-adhesion, such as experienced during the studies of Singamneni et al. [94,95]. This aspect is equally critical for both FGF and FFF processes. The flexibility and ease of implementation of medium scale class extruders is further exemplified by the study of Hertle et al. The extruder was mounted on 6 axis robotic arm to 3D print PP strands sheet on an aluminium substrate [96]. This innovative study evaluated the bond strength between these two materials and demonstrated the applicability of FGF beyond conventional 3D printing.

The reduction of weight and size was a common goal that drove the studies of La Gala et al. [44,97] and Khondoker and Sameoto [39]. These teams developed two radically different solutions for the same problem. The research team of La Gala et al. [44,97] proposed a conical extruder, shown in Fig. 13, which allows for a longer screw path in a more compact extruder configuration. The system managed to extrude ABS and polystyrene (PS) with less degradation than in FFF, the same result as reported by Liu et al. [79] with small-scale extruders. The main limitation is the increased manufacturing complexity especially when it comes to the critical barrel to screw clearance. Furthermore, the use of a large diameter at the feeding end, may limit the extruder's capability in generating pressure. The other solution developed by Khondoker and Sameoto [39] involved the use of a static screw extruder with a flexible heated hose to deliver the melt to the deposition head during 3D printing. This setup was used to successfully 3D print elastic inflatable actuator (EIA) using SEBS and shape memory polymers [98]. The most significant issues that may hinder this setup is the extended residency

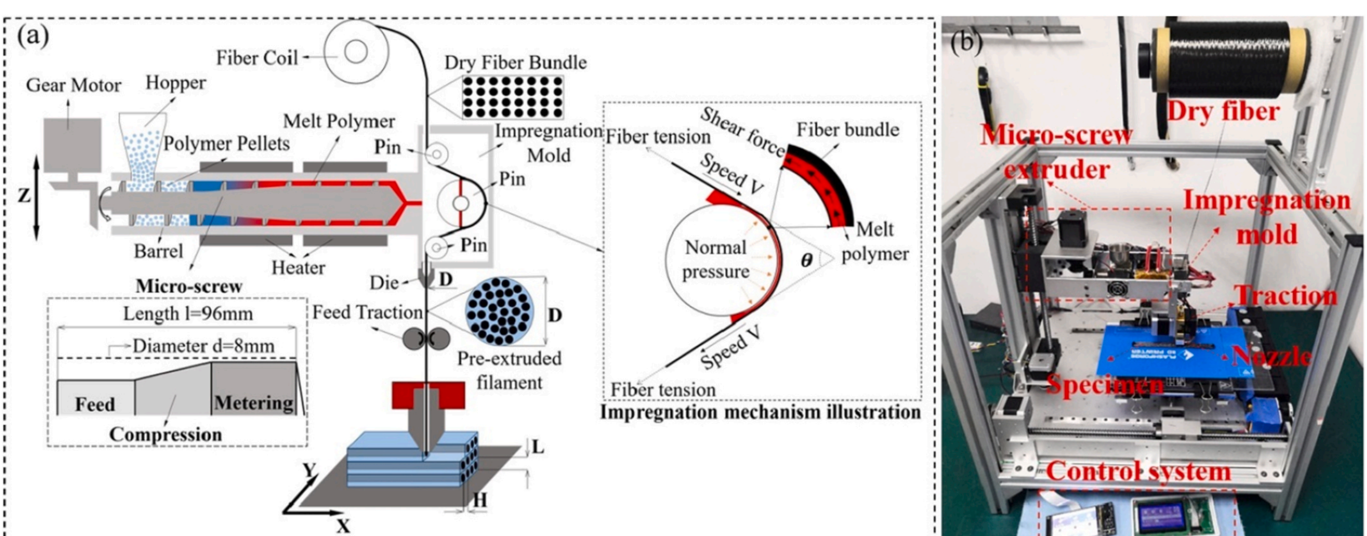

Fig. 12. Schematic (a) and equipment (b) of micro-screw in-situ extrusion based 3D printed continuous fibre reinforced composites adopted from Ref. [37].

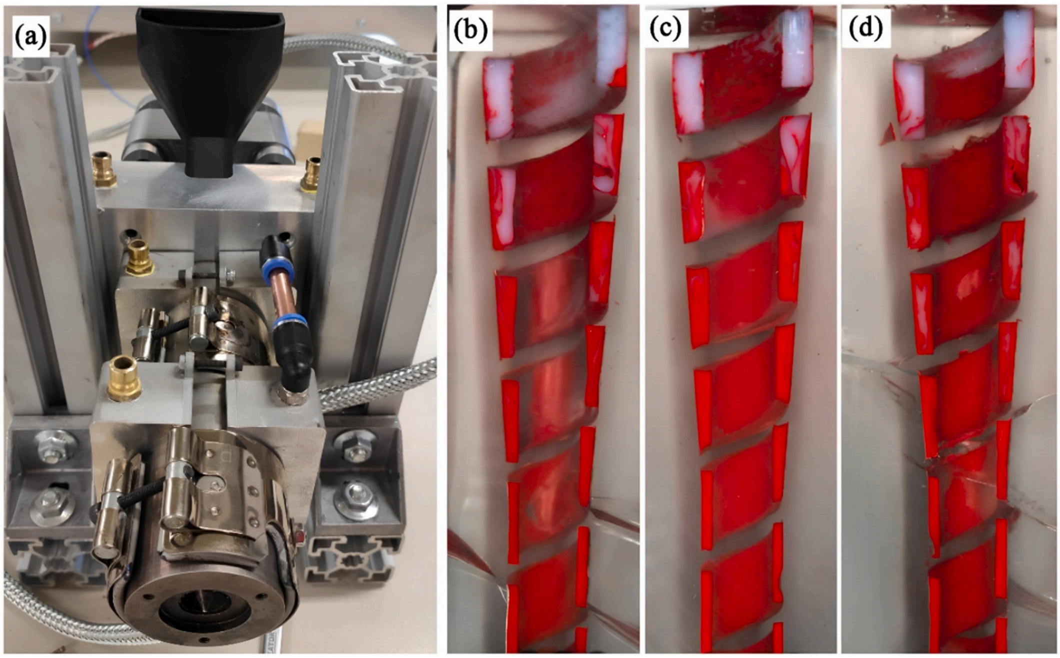

Fig. 13. Micro-extruder cooling setup for screw-freezing experiments and (b to d) embedded samples for ABS at screw frequency of 2, 5, and 8 rpm, adapted from Ref. [97].

time of the material which may lead to undesired degradation along with the added energy consumption of the heated hose.

A more recent study brought forward by Lu et al. [36] has further advanced the research area by enabling online mixing of high performance thermoplastics with fibre reinforcement. The extruder comprised of two horizonal feeding screws and one main vertical mixing and plasticating screw, as shown in Fig. 14. The study used PEEK powder and carbon fibre (CF) 50 wt%/PEEK 50 wt% powder as the two feedstock materials. Whilst the system successfully 3D printed at different concentrations, increasing CF concentration led to an increase in porosity caused by an increase in viscosity. This indicates that further studies possibly with longer screws may be necessary to improve compression and thus decrease undesired porosity of the composite extrudate.

This section demonstrated various novel medium-scale FGF extruder designs, all of which involved modifications to the single screw extruder configuration. With sufficient research, these innovative designs could potentially be miniaturized to the small-scale class. Miniaturizing the technology enhances accessibility, while scaling up increases throughput and enables the fabrication of larger objects.

6.4. Large scale

Large-scale extruders make use of extrusion screws which are longer than 200 mm. These extruders employ stronger motors which, combined with the longer screws, can drive a greater throughput with a greater degree of plasticating and mixing. These aspects make large-scale extruders critically different than the other classes, with their own benefits and trade-offs.

A classic example of a large scale FGF 3D printer is the Fused Form FF600+ [99] which uses a single screw extruder mounted in a closed chamber. Mazzei Capote et al. [100] used this system to 3D print ABS with barium titanate ceramic and a plasticizer to reduce its complex viscosity. A distinctive extruder is the Massive Dimensions MDPH2, which operates at speeds between 25 and 200 RPM [101], unlike most extruders that stay below 25 RPM [27]. This extruder was successfully used to produce PLA reinforced with continuous CFs [54,55]. Optimal CF deposition occurred at a 25° tilt, enabling higher printing speeds and better impregnation quality. However, the study did not show the CF's cross-sectional position in the extrudate, indicating the need for further research to improve understanding of fibre co-deposition.

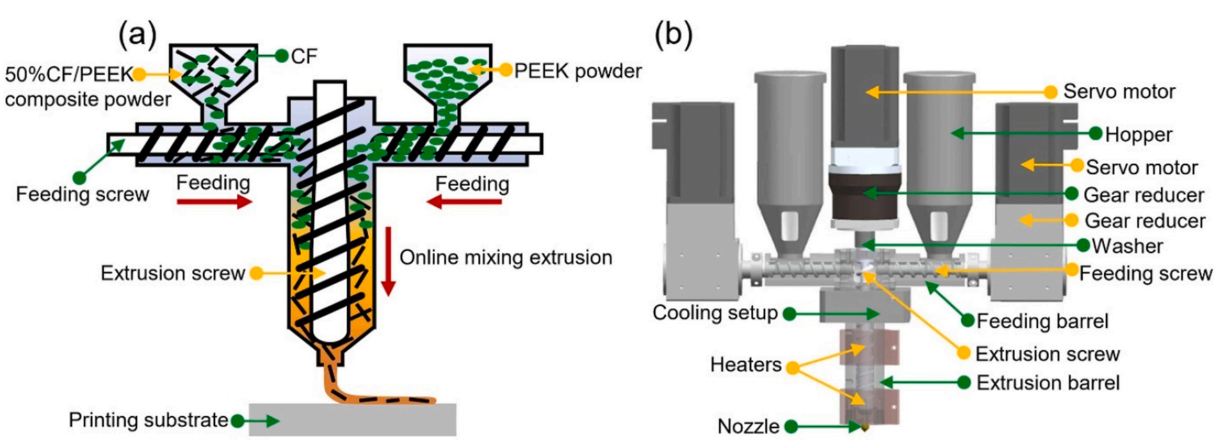

Fig. 14. Schematic of the screw-extruded online mixing 3D printhead (a) and the resulting 3D model (b) [36].

The Gigabot X is another classic large-scale system which has been used predominantly for studies involving recycled or regrind thermoplastic [6,7,102–105]. Byard et al. demonstrated that direct 3D printing with shredded polymer waste can yield cost savings compared to mass-produced products [6]. Another study by Little et al. [104] highlighted the difficulty of 3D printing using recycled polyethylene terephthalate (rPET) flakes on the Gigabot X printer with a 16 mm diameter screw. This required an extra feedstock crammer for rPET flakes, unlike when pelletized rPET was used. However, this result is inconclusive as flaky rPC [51,99] did not exhibit the same extrusion inconsistencies as flaky rPET [104]. The research team of Reich et al. managed to achieve similar properties to FFF PC [99]. This indicates that the problems associated with 3D printing of flaky rPET may not have been caused by the feedstock morphology but rather by the material itself. Larger extruders than the Gigabot X, such as the BAAM-100 by Cincinatti (USA), were more successful when 3D printing reground feedstock.

BAAM-100 by Cincinatti (USA) with a screw of 30 mm in diameter and 320 mm in length was found to be the extruder with the largest screw diameter applied for FGF. The larger screw diameter allowed for easy feeding and processing of regrind thermoplastics even when mixed with fillers such as CFs [53] and wood flour [52] without necessitating pre-compounding before 3D printing. When using the recycled granulates, the extrusion was consistent without any clogging [52,53], unlike when using a small-scale extruder as done by Alexandre et al. [78].

Large extruders are capable of large extrusion rates especially when using large nozzle diameters. The use of large nozzle diameters leads to a small surface area to volume ratio which in turn means that the extrudate takes a long time to cool down. A slow to cool extrudate coupled with a fast deposition rate often leads to warpage. This is a common issue with systems like the BAAM-100, caused by the high heat energy present in the large volume of extrudate, as shown in Fig. 15. Reinforcement using CF or glass fibre (GF) was found to improve thermal stability and decrease this warpage issue [51]. Studies conducted by Leander Schmidt et al. [106] and Merez Trejo et al. [50] aimed to minimise this warpage issue through modelling and thus account for the temperature build-up in the slicing process and by determining the max allowable extruder temperature respectively.

The research group of Brackett et al. [107] took fibre reinforcement a step further and studied 3D printing with functional gradient by transitioning from unfilled ABS to ABS with 20 wt% CF during print. The system was also employed to 3D print a high performance polymer polyphenylene sulfide (PPS) with 50 % CF [108]. Only 10 % of the data sheet strength was achieved. This was partly attributed to porosity but probably the largest contribution is the lack of heated chamber as observed when 3D printing PEEK [36,86,109,110]. The same chamber heating issue was noted by Barera et al. [111] when 3D printing polyamide 6 (PA6) compounded with 40 wt% CF using the CMS Kreator Ares. This underscores a gap in literature, as there is a lack of published studies developing layer or chamber heating system for large-format FGF 3D printing. This is necessary to improve the layer bond strength with similar materials. A different solution was proposed by Wang et al. [112] which would use specifically designed nozzle geometries that aimed to decrease the 3D printing porosity to then improve strength.

Beyond application of commercial large-scale extruders, a number of advancements have been made in the development of novel systems. Mi et al. [62] evaluated the effects on extrusion by adding an elongated blister ring at the end of the extrusion screw, as shown in Fig. 16. This extra section replaced part of the metering section with a shaft section instead of the extrusion screw thread. The new shaft section had a smaller diameter than the overall screw outer diameter. The thin gap created between screw shaft and barrel allowed for only a thin sliver of molten material to flow through, effectively shearing it. This resulted in an increase in extrusion consistency and blending but also an increase in polymer degradation possibility. The shearing screw also caused a higher degree of orientation of the molecule chains which increased tensile modulus and decreased elongation at break for rPP. The flow resistance caused by the shearing section led to a significant increase in the necessary screw speed for the same extrusion rate, increasing from 11.7 to 39 RPM respectively.

Extruder designs for large format 3D printing do not necessarily have to be heavy neither require a bulky motion system. One solution to this problem was provided by Rattan et al. [113] which implemented the Hangprinter system by Tobben [114], as shown in Fig. 17. A hangprinter is a cable driven motion system, allowing large volume printing., It was originally designed for lightweight extruders but this development by Rattan et al. has brought about this low-cost motion system for FGF, at

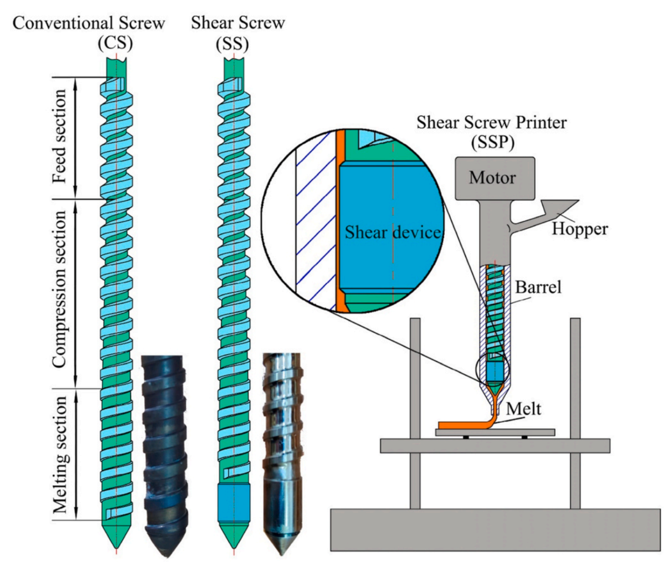

Fig. 16. – Schematic representation of conventional screw (CS), shear screw (SS), and shear screw printer (SSP), adapted from Ref. [62].

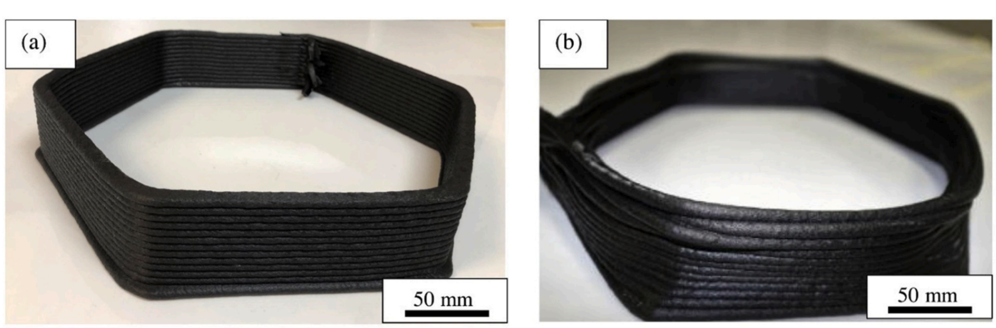

Fig. 15. Hexagon geometries printed with a BAAM machine. Frame (a) depicts a hexagon printed with a 90 s delay between layers, while frame (b) depicts a hexagon geometry printed with no added layer time. Notice the difference in print quality where the part shown in (b) is defective, adapted from Ref. [50].

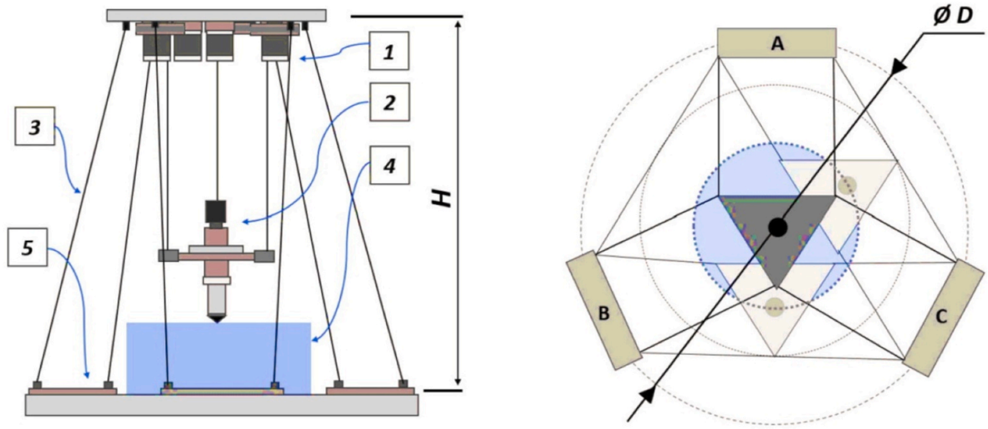

Fig. 17. Waste plastic FGF/FPF Hangprinter schematic where (1) ceiling unit housing controls and 4 motors for A, B, C and D axes; (2) end effector with FGF/FPF extruder; (3) A, B, C, and D lines/cables; (4) scalable, conical build volume and (5) print bed and ground anchors, adapted from Ref. [113].

about €2000. The accuracy achieved was less than that of a conventional desktop system, reaching at best ~0.1–0.3 mm absolute error. This value can be improved by implement an already existing optical positioning system called the hp-mark developed by Tobben [115]. Even if the accuracy and reliability of the system never reaches the same level as that of a rigid motion system, the cost savings are significant enough to make the product worthwhile.

High-performance polymers like PEEK are among the most challenging thermoplastics to 3D print. Tseng et al. [109], Hu et al. [8], and Li et al. [116] studied unfilled PEEK [109], PEEK with up to 30 wt% CF [8], unfilled PA6, and PA6 with up to 33.6 wt% CF [116]. Tseng et al. utilized infrared (IR) lamps, while Hu et al. employed an enclosed heated chamber reaching 200 °C and a heated bed at 250 °C to improve mechanical properties. Both studies with CF reported lower extrudate density and increased porosity with higher CF content, attributed to the higher viscosity preventing trapped air bubble release. Despite underperforming compared to injection molded specimens, the filled specimens achieved higher strength than all the previous MEX studies [8, 116]. However, all tests were conducted in the XY plane, ignoring expected material anisotropy. Future research work is necessary to elucidate this important aspect of the 3D printed product's mechanical properties.

6.5. *Unclassified*

6.5.1. *Commercial*

All the journal articles covered till to date included information about the extruder design, which eases the classification of extruders. The remaining 57 articles did not have any information openly available and therefore were classified based on common traits with other similar extruders with known dimensions. Out of these articles, 19 of them used custom developed FGF systems, whereas the rest employed commercially available systems of various sizes.

Of the small FGF commercial systems there are 5 namely Direct 3D [117], Creality G5 [118], Brinter [119], 3D Cultures [120] and 3D Discovery by RegenHU [121]. Daniele et al. [122] employed the Direct 3D [117] system to demonstrate that recycled high density polyethylene (rHDPE) can be 3D printed and that the addition of 15 % wt.% GF countered degradation by doubling the elastic modulus and increased yield strength. Another study by Wang et al. [31] used the Creality G5 [118] to successfully 3D print polyphenylene sulphide (PPS) with graphene nanoplatelets (GNPs). Immonen et al. [29] also studied composites 3D printing using the Brinter [119] and showed that the addition of plasticizer to cellulose acetate propionate was necessary to enable self-adhesion. Further studies on composite 3D printing were carried out with the 3D Discovery by RegenHU [121] to produce scaffolds made out of PCL with graphene [123] and with carbon nanotubes and nano-hydroxyapatite [124]. In the same year, Huang et al. [125] published another study using unfilled PCL to produce scaffolds and subsequently laying down fibrils using electrospinning. The research team of Lee et al. [126] pushed the research boundary of small scale FGF by 3D printing hybrid piezo-magnetic self-sensing actuators (HPSMA) using the Pellet Extrusion Bioprinter by 3D Cultures. Despite this positive result the study reported that immersion precipitation 3D printing was found to be a superior solution than FGF to produce HPSMA. The result of this article is a reminder that whilst FGF is a versatile technique, it is not always the best tool for a given application.

The medium scale is more difficult to identify especially for those systems which are close to either end of the spectrum. Out of the remaining FGF systems, 3 commercial systems were found namely, PAM series P and Lx [127], Ambit extruder [128] and the Cosine AM1 3D printer [129]. The PAM series offer off the shelf FGF 3D printers that can produce multi-material parts through multiple extruders. This feature was used by Yousfi et al. [130] and Andreu et al. [131] to study poly-methyl methacrylate (PMMA)/PLA layered structures and poly(d,l lactide) (PDLLA) with different combinations of hydroxyapatite (HA) and bioactive glass (BG) respectively, as shown in Fig. 18. These functionally graded materials were found to have transitional mechanical properties

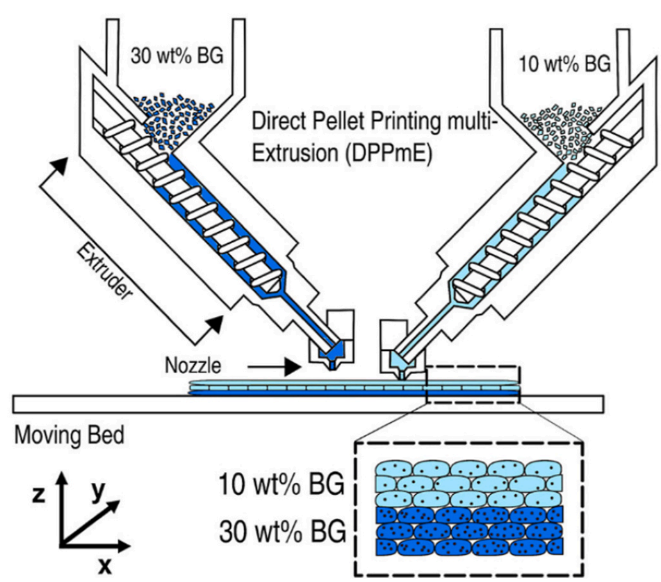

Fig. 18. Schematic representation of direct pellet printing multi-extrusion process with 10 and 30 wt % of bioglass, adapted from Ref. [131].

of each material's distinct properties.

The PAM series 3D printers were also used in single extrusion mode using polylactic-co-glycolic acid (PLGA) [132], EVA with fire-retardant [9], rPP and PP with glass fibres and mineral fill [133], and 85 wt% of zirconia powder with 15 wt% PA [134]. Similar to as reported by Andreu et al. [131] that used PDLLA, Gradwohl et al. [134] also reported degradation of PLGA when using FGF. On the other hand, 3D printing the same material using FFF resulted in less degradation due to shorter residence time and less shearing involved. Degradation studies using powder and small-scale extruders with a smaller screw have shown the opposite effect i.e., the FFF products degraded more [78,79]. High filler content materials such as produced by Spitaels et al. [134] where the PAM series MC was used to 3D print 85 wt% of zirconia powder with 15 wt% PA produced poor 3D printing quality, but this was expected due to the low thermoplastic content.

Montoya-Ospinai et al. [135] also studied novel additives. The research team employed the Cosine AM1 to 3D print HDPE with vitrimers. This resulted in decreased part warpage and improved self-adhesion during the 3D printing process, compared to virgin HDPE. The vitrimers also decreased anisotropy when the parts are heat-treated after 3D printing. A diverse 3D printing approach was studied by Northup et al. [136] using the Ambit extruder in a milling machine [128]. The system was used to3D printed a mold which was then post-machined to improve surface finish.

The remaining large-scale commercial FGF systems are presented in this section. Of these, there are 15 different studies, with 8 distinct 3D printing systems. The Super Discovery 3D Granza was used by Moreno Nieto et al. to 3D print furniture for naval applications using PLA/ABS blend with fire retardant [137]. This study demonstrated the capacity of large scale FGF to 3D print large objects, but it also highlighted the necessity for post-processing, especially when a smooth surface finish is necessary. The same system was used to 3D print using acrylonitrile styrene acrylate (ASA) with 20 wt% CF [138], PLA and rPLA with titanium (IV) nanopowder [34], and ABS with 20 wt% CF [139]. The addition of titanium (IV) nanopowder to recycled PLA increased thermal stability and crystallinity and countered the loss of mechanical properties brought about by thermoplastic degradation caused by the remelting process necessary for recycling [34].

The researchers at Politecnico di Milano delved further into large format 3D printing by using unfilled regrind PLA [140] and with the addition of spent coffee grounds [59]. These studies were conducted with the Delta Wasp 3 MT. Romani et al. [140] demonstrated that after six 3D print and regrind cycles, each time using the same batch of material, there was a decrease in mechanical properties and only minor variations in thermal properties. The addition of spent coffee grounds by Paramatti et al. [59] to PLA led to an increase in flowability and layer adhesion, whilst achieving good 3D printability. Another important filler is GF which, as shown by previous studies, can improve thermal stability. Winter et al. [141] using the Delta Wasp 3 MT and Austermann et al. [142] with the Extruder 500-CU-D by Yizumi, also used this filler to reduce the warpage of PP. Globular or powder fillers, namely talcum powder and glass bubbles did not demonstrate a similar improvement in warpage behaviour [141]. To minimise the occurrence of pores brought about by the addition of fibre reinforcement, Sayah and Smith [143] proposed compressing the extrudate by using a roller to decrease porosity.

More studies with novel materials were published by Lengauer et al. [144] which used an ExAM 255 printer by AIM3D to produce hardmetal and cermet bodies and by Zlatanovic et al. [145] with the ExOn10 using aliphatic polyketones (PK). The former study demonstrated the material flexibility of FGF by adding metal injection molding pellets as another possible 3D printing material. The latter study also opened further the material's library by introducing aliphatic PK which have good chemical resistance and better mechanical properties than PA12. This could be done at a lower cost and with 61 % lower environmentally harmful emission created during its production process.

Finally, the study by Leschok et al. [146] developed an innovative 3D printing approach, using a well-known device, the annular die. The research group used a SAEKI robotics FGF system to deposit hollow tube extrudates in different patterns, as shown in Fig. 19. This novel printing technique allowed for light weight 3D printing of large objects, using PETG, PLA, cyclic olefin copolymer (COC) and PP. To produce hollow tube extrudates, the extrudate was pressurised with an internal stream of air, otherwise it would flatten out. Studies such as by Leschok et al. [143] greatly expand the capabilities of AM, demonstrating that the subject merits further research as there are still novel techniques that may be developed.

6.5.2. Custom

In some cases, even published research articles that made use of custom developed FGF systems, failed to report the dimensions of the extruder. These studies all used FGF extruders purely as tool and did not try to optimise or otherwise improve the technology itself.

When it comes to small-scale FGF, three studies were found, all of which used novel material combinations. The study by Yu et al. [32] demonstrated that reactive compatibilization of PLA with up to 3 wt% polybutylene adipate-co-terephthalate (PBAT) blends using vinyl-functionalized graphene oxide (VGO) nanosheets had higher impact strength and increased the crystallinity of PLA. A separate study by Mondal et al. [147] produced magnetorheological elastomers using SEBS thermoplastic elastomer (TPE). This study determined that the infill density can be used to tune the magnetorheological stiffening effect when using a hexagonal infill structure. Another study by Brooks et al. [148] produced biopolymer thin shells on a curved, hemispherical mandrel. Another novel configuration, 4 axis, 3D printing system was developed by the research team of Wang et al. [149] that used a medium scale extruder for the production of poly(L-lactide) PLLA and PCL cardiovascular stents with zero Poisson's ratio in longitudinal deformation. The 4th axis comprises of a rotating mandrel upon which the cylindrical stent was 3D printed.

When it comes to large-scale FGF extruders, one of the first studies on the subject was brought forward by Reddy et al. [150], back in 2007. The study used ABS to optimise nozzle temperature, chamber temperature and strand to strand gap for improved bond strength and surface finish. A layer study by Akbari et al. [151,151] developed a thermal simulation strategy using finite element analysis to reduce the occurrence of thermal warpage. This approach was justified due to the long extrudate cooling time which was found to be around two orders of magnitude longer than that of small scale FGF. Another challenge of large scale FGF which is in common with all MEX scales is the capability of the system to produce overhangs. This issue was studied by Krčma and Paloušek [152] using a 5 axis robotic arm to control the movements of the extruder. The study achieved a greater overhang angle of 75° when using a 5 axis, non-planar 3D printing methodology. In contrast, the classic 3 axis planar only managed to print features with a 30° overhang.

An interesting study by Romeijn et al. [153] evaluated instantaneous and time-dependent mechanical properties on PETG specimens 3D printed using a 5 mm nozzle. The results that used time temperature superposition technique for creep were rather limited as the creep experiments conducted at 65 °C did not superimpose on the lower temperature experiments. This is the only published study on long-time dependent mechanical properties concerning FGF. This kind of research is necessary if products are to be made with intention to last.

The last article of interest is different from all the rest as it concerns the implementation of a pump to FGF systems. This study, presented by Canessa et al. [38], aimed to create a known volumetric extrusion rate by employing the use of a Moineau pump using the design shown in Fig. 20. The system was only used with chocolate and wax and managed a consistent extrusion rate. Further work on this type of design is necessary if such a system would ever be useable for thermoplastic polymer FGF. The added manufacturing complexity brought about by the Moineau pump geometry may also make this extruder design

Fig. 19. (a): Hollow-Core 3D printing nozzle with a 24 mm orifice and a 2 mm wall thickness. (b): Extruded PETG bead. (c): 3D printed sample, cut, with a hand to represent scale and transparency, adapted from Ref. [146].

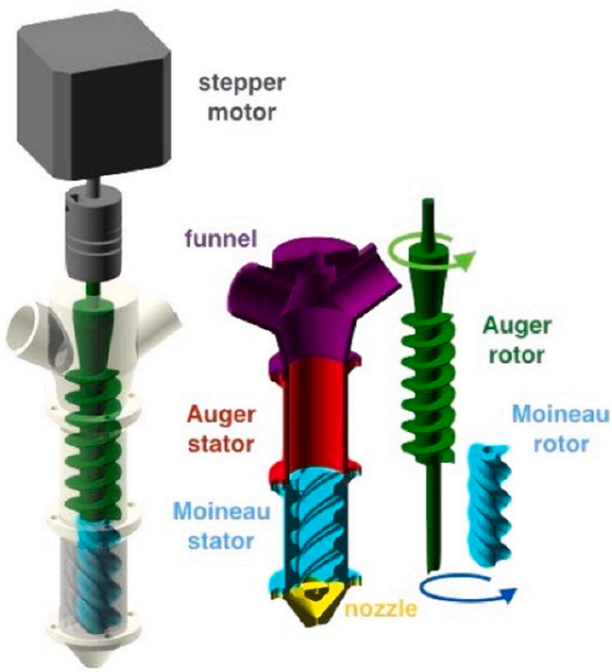

Fig. 20. Schematics of a pellet extruder, combining together Auger and Moineau screws [38].

undesirable.

7. Conclusion

Fused Granulate Fabrication (FGF) has shifted from traditional applications like PCL scaffold fabrication to a contemporary focus on recycling and performance. This growing interest is evident in the increasing number of published studies and innovations in extruder design in the last decad.

A new classification system for FGF extruders was proposed, categorizing them by screw diameter and length into three classes: small-scale extruders with screws up to 100 mm in length, medium-scale extruders with a screw length from 100 to 200 mm, and large-scale extruders with a screw length of over 200 mm. Additionally, powder extruders are classified separately, defined by a screw diameter of 7 mm or smaller. While this classification provides a useful framework, there are outliers in each class, which is typical in a rapidly evolving field like FGF.

FGF's materials library now includes high-performance polymers and composites, including fibre reinforcement. However, powder extruders remain specialized for heat-sensitive materials due to their low residency time, excelling in personalized medicine and scaffold production. Small-scale extruders are widely used to 3D print elastomers and even high-performance thermoplastics, usually focusing on small products akin to desktop FFF. Medium-scale extruders can be seen as innovative test beds for scaling technology. Large-scale FGF systems excel in large-format printing and extrusion of reinforced thermoplastics, but still face challenges such as thermal warpage.

Future FGF research should focus on miniaturizing small-scale extruders while keeping costs low and maintaining process capabilities. For large-scale extruders, the goal is to reduce size, weight, and complexity while increasing throughput. These advancements would lower costs, enhance capabilities, and broaden the technology's commercial viability. The use of recycled thermoplastics, particularly regrind materials, is an expanding research area that supports a circular economy across FGF classes. Another emerging field involves in-process mixing of multiple components, such as thermoplastic matrices with CF reinforcement. In conclusion, FGF is a rapidly growing research area with a broadening user base, contributing to a more sustainable future, which aligns with contemporary policy goals of many advanced economies.

CRediT authorship contribution statement

Albert Curmi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arif Rochman:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.polymer.2025.128459.

Data availability

Data will be made available on request.

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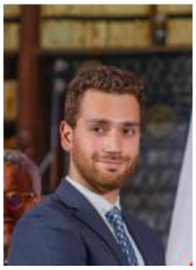

Mr. Albert Curmi; Mr. Albert Curmi is a PhD candidate at the University of Malta specializing in additive manufacturing and polymer processing. He holds a first-class honors degree in Mechanical Engineering from the University of Malta. Currently in the final year of his PhD, his research focuses on screw extrusion fused granulate fabrication for additive manufacturing.

With over four years of experience as a researcher at the University of Malta, Mr. Curmi's expertise spans additive manufacturing, polymer processing, development of additive manufacturing extruders, material characterization, and simulation. His work has a particular emphasis on high-performance thermoplastics like polyether ether ketone (PEEK) and ULTEM 9085, as well as elastomers. His research activities encompass process development, material characterization, and application-focused innovation.

Mr. Curmi has conducted extensive studies in Rapid Tooling (RT), Rapid Prototyping (RP), and Rapid Manufacturing (RM), specifically using thermoplastic molds for injection molding. His material characterization expertise includes rheometric testing, infrared and Raman spectroscopy, energy dispersive spectroscopy, and tensile and shear testing, among others.

His contributions have led to several peer-reviewed journal publications and conference presentations. Beyond academia, he actively disseminates his research through general articles, media campaigns, and public engagement events like Science in the City.

Mr. Curmi has been integral to numerous multi-disciplinary research projects. Notable among these are:

•**BioSA Project**: He contributed to the design and fabrication of 3D-printed polymer implants, later coated with metal powder and sintered. His responsibilities included experiment design, practical lab work, and material development.

•**MALTI3D Project**: As the main researcher, he spearheaded the development of a novel screw extrusion 3D printer with a 5-axis system, overseeing design, technology development, lab work, and project management.

•**REO3D**: Introducing online rheometry to 3D printing.

Mr. Curmi's work continues to contribute to the advancement of thermoplastic additive manufacturing, with a focus on improving processes, materials, and applications in this rapidly evolving field.

Prof. Arif Rochman; Prof. Arif Rochman is an Associate Professor at the Department of Industrial and Manufacturing Engineering (DIME) at the University of Malta, specializing in polymer engineering and additive manufacturing.

He began his academic journey with a Dipl-Ing. (FH) degree in Aeronautical Engineering from the University of Applied Sciences Munich, Germany, in 2000. His undergraduate thesis, completed at DaimlerChrysler Aerospace in Ottobrunn, focused on the failure analysis of fire-protected glass fibre reinforced plastic (GRP), sparking his interest in lightweight structures and long-fibre reinforced plastics.

Driven by this passion, Prof. Rochman pursued postgraduate studies in Polymer Technology at Aalen University, Germany, earning an MSc degree in 2002. He subsequently joined the Institute of Polymer Science and Processing at Aalen University, contributing to research projects on polymer processing, material testing, and simulation.

In 2010, Prof. Rochman obtained his PhD from Queen's University Belfast, UK. His doctoral research introduced a patented processing method, Thermo Flow Forming (TFF), which enables the production of thin-walled micro-components from high-performance polymers that are otherwise challenging to process using conventional injection molding.

Since 2009, Prof. Rochman has been part of the University of Malta, where his research focuses on polymer processing, additive manufacturing, and material characterization. He supervises multiple undergraduate, MSc, and PhD research projects in additive manufacturing, exploring applications in rapid prototyping (RP), rapid tooling (RT), and rapid manufacturing (RM). His work has led to numerous peer-reviewed publications in international conferences and journals.

Prof. Rochman has played a pivotal role in several nationally funded research projects. These include:

•**BioSA**: Developing 3D-printed polymer templates for subsequent powder metallurgy in fabricating metal implants. • LASeeeR: Creating filaments with enhanced absorption of near-infrared light for laserassisted 3D printing.

•**MICORE**: Investigating 3D-printed cores for micro-injection molding.

Currently, he coordinates and leads innovative projects such as:

•**SPELL3D**: Developing a novel 3D printer.

•**MALTI3D GoToMarket**: Creating a multi-material, multi-axis fused granular fabrication (FGF) 3D printer.

•**CONFORM**: Designing additively manufactured metal injection mold inserts with advanced conformal cooling channels.

•**REO3D**: Introducing online rheometry to 3D printing

•**VACUUM**: Improving venting in injection molding.

He is also involved in a number of projects covering different subjects, such as biomedical implants, thermoplastic recycling and rubber 3D printing. Prof. Rochman's contributions continue to shape advancements in polymer engineering and additive manufacturing, bridging academic research with industrial applications.