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Energy consumption and carbon footprint of 3D printing in pharmaceutical manufacture

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ABSTRACT

Achieving carbon neutrality is seen as an important goal in order to mitigate the effects of climate change, as carbon dioxide is a major greenhouse gas that contributes to global warming. Many countries, cities and organizations have set targets to become carbon neutral. The pharmaceutical sector is no exception, being a major contributor of carbon emissions (emitting approximately 55% more than the automotive sector for instance) and hence is in need of strategies to reduce its environmental impact. Three-dimensional (3D) printing is an advanced pharmaceutical fabrication technology that has the potential to replace traditional manufacturing tools. Being a new technology, the environmental impact of 3D printed medicines has not been investigated, which is a barrier to its uptake by the pharmaceutical industry. Here, the energy consumption (and carbon emission) of 3D printers is considered, focusing on technologies that have successfully been demonstrated to produce solid dosage forms. The energy consumption of 6 benchtop 3D printers was measured during standby mode and printing. On standby, energy consumption ranged from 0.03 to 0.17 kWh. The energy required for producing 10 printlets ranged from 0.06 to 3.08 kWh, with printers using high temperatures consuming more energy. Carbon emissions ranged between 11.60 and 112.16 g CO_2 (eq) per 10 printlets, comparable with traditional tableting. Further analyses revealed that decreasing printing temperature was found to reduce the energy demand considerably, suggesting that developing formulations that are printable at lower temperatures can reduce CO_2 emissions. The study delivers key initial insights into the environmental impact of a potentially transformative manufacturing technology and provides encouraging results in demonstrating that 3D printing can deliver quality medicines without being environmentally detrimental.

1. Introduction

Three-dimensional (3D) printing is an advanced manufacturing technology achieving remarkable breakthroughs in healthcare (Awad et al., 2021b; Heuer et al., 2019; Kholgh Eshkalak et al., 2020; Osouli-Bostanabad et al., 2022; Rezvani Ghomi et al., 2021). In pharmaceutics, digitalised technology has several advantages, including precision, personalisation and speed (Awad et al., 2021a; Elbadawi et al., 2021a; Liang et al., 2019). Moreover, 3D printing can be considered an environmentally-friendly manufacturing process, because it can reduce the amount of material waste generated during use. Traditional manufacturing methods, such as injection moulding, often involve cutting away excess material or creating moulds that are discarded after a single use. With 3D printing, however, only the amount of material needed to create the final product is used. Additionally, 3D printing can reduce the environmental impact of transportation because the production of complex parts can be achieved locally, (Jandyal et al., 2022; Nadagouda et al., 2020). To date, the technology has been successfully demonstrated to produce microneedles, stents, films and catheters (Chen et al., 2020; Elbadawi et al., 2021b; Maity et al., 2021; Pere et al., 2018).

3D printing is a collection of technologies that produce 3D structures by different means. Examples of printing technologies that can be used for producing medicines include fused deposition modelling (FDM) (Berger et al., 2023; Elbadawi et al., 2020; Goyanes et al., 2014; Melocchi et al., 2015; Skowyra et al., 2015), stereolithography (SLA) (Karakurt et al., 2020; Li et al., 2020a; Li et al., 2020b; Xu et al., 2020), direct ink writing (DIW) (O'Reilly et al., 2021; Picco et al., 2022; Picco et al., 2023; Utomo et al., 2023; Wan et al., 2020), direct powder extrusion (DPE) (Boniatti et al., 2021; Goyanes et al., 2019) and selective laser sintering (SLS) (Abdalla et al., 2023; Allahham et al., 2020; Fina et al., 2018; Hamed et al., 2021). Research into 3D printing of

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medicines has been conducted for over three decades but its current popularity has been driven partly by the US Food and Drug Administration's (FDA) approval of Spritam® in 2015, which was the first commercial product produced with 3D printing and has shown its potential as a viable commercial manufacturing option (Fitzgerald, 2015). More recently, the FDA has given investigational new drug (IND) clearance on three printed medicinal products by Triastek, Inc. 3D.

However, 3D printing also has some negative environmental impacts to consider. One of the main concerns is the emissions generated by the printing process. Many 3D printers use plastics as their primary building material, and the process of melting these plastics to create parts can release harmful chemicals into the air.

Another concern is the energy consumption of 3D printers. Some 3D printers require a large amount of energy to operate, and if the energy used comes from non-renewable sources, it can contribute to climate change; hence there is a strong drive to develop environmentally sustainable technologies (Berrang-Ford et al., 2019). Many major economies are steadfastly aiming to achieve carbon neutrality over the next few decades (Malik et al., 2018; Marteau et al., 2021; Wu, 2019). Carbon neutrality, also known as net-zero carbon, refers to the balance between the amount of carbon dioxide released into the atmosphere and the amount removed from it. Achieving carbon neutrality is seen as an important goal in order to mitigate the effects of climate change, as carbon dioxide is a major greenhouse gas that contributes to global warming. Many countries, cities, and organizations have set targets to become carbon neutral by a certain date in the future. For example, the UK's National Health Service has set a deadline for reaching zero carbon emission by 2050 and will prioritise partnering companies that are also carbon neutral (Jennings and Rao, 2020). Likewise, major pharmaceutical companies have declared similar goals to reduce their carbon emissions (Carpenter, 2021). While sectors such as transportation (Bonsu, 2020; Davis et al., 2018), manufacturing (Chen et al., 2022; Okorie et al., 2023) and mining have begun to take action by optimising their energy demands or integrating enabling technologies, the issue has received little attention in the pharmaceutical sector (Chaturvedi et al., 2017; Wu et al., 2022), despite it being an energy-intensive industry, emitting around 55% more CO_2 than the automotive industry (Belkhir and Elmeligi, 2019; Chen et al., 2023).

Some work on the environmental impact of 3D printing has been reported, for instance on optimising drug release profiles (Economidou et al., 2021; Sadia et al., 2018). However, if 3D printing is to be incorporated more widely into commercial manufacturing or hospital settings, then its environmental impact must be more fully quantified and understood. As a digitalised technology, 3D printing depends on electricity to operate, and electricity is a main contributor to CO_2 emissions (Gao et al., 2019). Some 3D printers require a large amount of energy to operate, and if the energy used comes from non-renewable sources, it can contribute to climate change.

Therefore, to begin to understand the environmental impact of 3D printed medicines, the present study investigated the energy consumption of 3D printer types commonly used in producing medicines. Energy consumption data allow for a sound approximation of the carbon emitted. Power usage was measured for printers on standby and during printing and, where possible, the effect of printer settings on minimising energy consumption was determined. The data provide a framework against which environmental impact strategies for the use of 3D printing commercially can be made, and suggest formulation methodologies that might be employed to minimise environmental impact while retaining pharmaceutical product quality and efficacy.

2. Experimental procedure

2.1. Energy consumption and CO_2 emission

Energy consumption was measured using an energy meter (Electrocorder AL-2VA, Acksen Ltd) with a sampling rate of 2 s. The CO_2 equivalent factor (CO_2 eq) was set to 0.19338 kge/kWh, taken from the UK's Department of Business, Energy and Industrial Strategy (BEIS) greenhouse conversion report (Department of Business, 2022).

2.2. Printers

Six benchtop printers were used for this study; a small FDM (mini Prusa, Prusa Research), a large FDM (Ultimaker S5, Ultimaker, Netherlands), DIW (BioX, Cellink, Sweden), SLS (Sintratec kit, Sintratec AG, Germany), SLA (Proxima 6, Voxelab, Serbia) and DPE (3D Limitless, Spain). The energy consumption of two supporting devices, a hot melt extruder (HME; Noztek, UK) in standby and between 75 and 175 °C, and a curing oven (Form Cure, Formlabs, USA) were also measured, since these are necessary adducts to FDM and SLA printing respectively. For each printer, the energy required to fabricate 10 printlets, each of which were 10 × 3 mm in size (designed using OnShape v1.150 and exported as an.stl file) was recorded. The six printers were operated using different softwares, as detailed below, which controlled both the printing parameters and performed the slicing. No supports were featured into the printing parameters.

– SLA

The SLA printer was operated using Chitubox v1.9.4. The printing parameters for the 10 printlets were; Set to layer height: 0.15 mm, Exposure time: 50–150 s.

– SLS

The SLS printer was operated using Sintratec Central v1.2.0. The printing parameters for the 10 printlets were; Layer height: 0.15 mm, Perimeter: 1, Laser speed: 100 mm/s, Heating chamber temperature: 80 – 180 °C.

– Small FDM

The small FDM printer was operated using the PrusaSlicer 2.5.0. The printing parameters were; Infill density: 75%, Infill pattern: rectilinear, Layer height: 0.15 mm, Printing speed: 80 mm/s, Built-plate temperature: 60 °C, Nozzle temperature: 75–200 °C, Nozzle diameter: 0.4 mm. The nozzle was made of brass.

– Large FDM

The large FDM printer was operated using Cura 5.1.0. The printing parameters were; Infill density: 75%, Infill pattern: rectilinear, Layer height: 0.15 mm, Printing speed: 80 mm/s, Built-plate temperature: 60 °C, Nozzle temperature: 75–200 °C, Nozzle diameter: 0.4 mm. The nozzle was made of brass.

– DIW

The BioX was operated using the on-board software. The printing parameters were; Infill density: 75%, Infill pattern: rectilinear, Layer height: 0.15 mm, Printing speed: 50 mm/s (the maximum allowed), Built-plate temperature: Room temperature, Printing pressure: 50 kPa, Nozzle temperature: RT-65 °C, Nozzle diameter: 0.4 mm. The nozzle was made of polypropylene.

– DPE

The DPE was operated using Repetier Host v2.1.3. The parameters set were; Infill density: 75%, Infill type: rectilinear, Layer height: 0.15 mm, Printing speed: 80 mm/s, Nozzle temperature: 75–200 °C, Nozzle diameter: 0.4 mm. The nozzle was made of stainless steel.

3. Results

The printers evaluated in this study operate on different principles and so have different energy requirements. In all cases there is the need for linear actuation in order to create the object being printed, but in the case of FDM, DPE and DIW printing there is a requirement for the printhead, and in some instances the build plate, to be heated and both SLS and SLA printing require the operation of a laser. Additionally, two of the printing technologies require ancillary equipment; preparation of the feedstock polymer filaments for FDM printing requires a hot-melt extruder and objects made with SLA printing are post-cured in an oven. Thus, for these two technologies, the energy consumption of these extra pieces of equipment was accounted for.

3.1. Energy consumption during standby

As with most machines, 3D printers consume energy when in standby mode. The energy consumed ranged from 0.03 to 0.17 kWh across all six printers when measured for one hour, with DIW consuming the most (Fig. 1). The values for the FDM printers include a contribution from HME and a notable difference was observed between them, the small FDM consuming 62.5% less energy than the large FDM printer. The DPE printer, which is an evolution of FDM that extrudes filament directly, was found to consume the same amount of energy as the small FDM printer combined with the standby consumption of the HME, but less than the large FDM combined with HME. The SLS printer, despite being the largest by volume, consumed a comparable amount of energy to both the DIW and large FDM printer. The curing oven commonly used with SLA printing did not have a standby mode and so there was no contribution from it.

Calculated CO_2 emissions ranged from 5.98 to 33.89 g CO_2 (eq) per hour. These values allow projections of CO_2 emissions to be made over extended time periods; leaving the printers on standby for one day, one month and one year would lead to emissions of 143.52 to 813.36 g CO_2 (eq), 4305.6 to 24,400.8 g CO_2 (eq), and 51,667.2 and 292,809.6 g CO_2 (eq), respectively. Clearly, leaving the printers on standby for extended time periods is environmentally damaging and so the best option would be to ensure printers are powered down when not in use.

3.2. Energy consumption during printing

The energy demand for producing ten printlets was recorded for all six printers (Fig. 2). The measurements reflect the energy needed during the priming stage (e.g. heating up, calibration, etc.), the printing process, and any subsequent cooling down mechanisms. As noted above, the energy needed for any auxiliary equipment was also factored into the calculations. For all printers bar SLS, the energy consumption values varied from 0.06 to 0.58 kWh. Similar to the situation for standby mode,

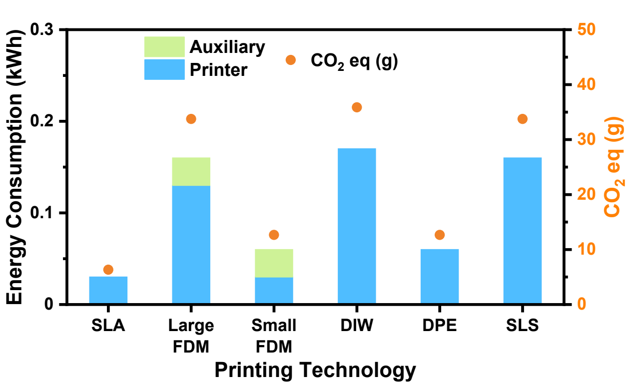

Fig. 1. Energy Consumption and calculated CO_2 emission for the printers during standby for one hour. The energy consumption of ancillary equipment is also shown.

a noticeable difference was observed between the two FDM printers, with the smaller printer requiring between 60.8% and 53.4% less energy than the large printer, depending on the HME temperature (high – 175 °C; low – 75 °C). The large difference is despite using similar printing parameters and the overall printing time being similar. The SLA printer required 0.14 kWh to operate, but sometimes heat is required for post-print curing (previous studies have post-cured SLA-printed drug delivery systems at 60 °C for 20 min, (Xu et al., 2021). With post-print curing, the energy consumption increased to 0.20 kWh, but even then SLA was still amongst the lowest energy-consuming processes.

The DPE printer required 0.22 kWh for printing, which is marginally more than printing with the small FDM printer combined with low temperature HME. However, the DPE printer required 56.9% less than energy than the large FDM printer combined with low temperature HME. The DIW printer consumed 0.21 kWh when the printhead was heated to 65 °C. However, unlike the other extrusion-based technologies, DIW can be operated without heat, and this mode required just 0.06 kWh. Hence, DIW technology consumed the least amount of energy. SLS printing, conversely, is energy-intensive, as it requires the whole printing chamber to be heated. It consumed 3.08 kWh, which was an order of magnitude greater than the other 3D printing technologies.

The Carbon emission values ranged between 11.60 and 595.61 g CO_2 equivalent per ten printlets (although excluding SLS from the data narrows the range to between 11.60 and 112.16 g CO_2 (eq) per ten printlets). Per printlet this equates to 1.16 to 11.21 g CO_2 (eq), values which are comparable to the 2.06–7.71 g CO_2 (eq) per tablet previously reported for a tableting machine (Hindiyeh et al., 2018).

3.3. The effect of operating temperature on energy consumption

For the material-extrusion based technologies (FDM, DPE and DIW), the printhead or nozzle temperature was varied. For the SLS printer, the chamber temperature was varied. The results presented in this section consider operation at the temperatures stated when monitored for 1 h, and do not take into account the time needed to heat up and cool down.

- FDM

Irrespective of the size of the printer, it is the printhead that is heated to allow the filament to extrude. Previous work has shown that printing temperatures can vary from 53 to 240 °C (Muñiz Castro et al., 2021), and so the values used herein covered this broad range. The time it took for the printhead to reach 200 °C was found to be less than 10 min, while following printing, the time needed for the printhead to cool down was also less than 10 min. Thus, the energy consumption during the heating and cooling periods were negligible.

The experiments conducted in Section 3.2 were performed with a nozzle temperature of 200 °C. Lowering the printhead temperature to 150 °C reduced the energy consumption of the large FDM printer by 6.25%, but operating at lower temperatures (100 and 75 °C) had no further effect on its energy usage (Fig. 3). The emission values were between 29.00 and 30.94 g CO_2 eq. For the same nozzle temperatures, the small FDM printer consumed less energy than the large FDM, with reductions of 73.3%, 66.67%, 60% and 43.75% at 75, 100, 150 and 200 °C, respectively (Fig. 4). There were more notable differences in the energy consumption data of the small FDM printer between the printing temperatures; reducing the printhead temperature from 200 to 150, 100, 75 °C resulted in 33.33%, 44.44% and 55.56% less energy demand respectively. The emission values were between 7.74 and 17.40 g CO_2 eq.

- DPE

In DPE a small auger is incorporated into the printhead that replicates the shearing process of HME, which allows powders to be mixed and extruded directly into the printer. Thus, the use of DPE requires a

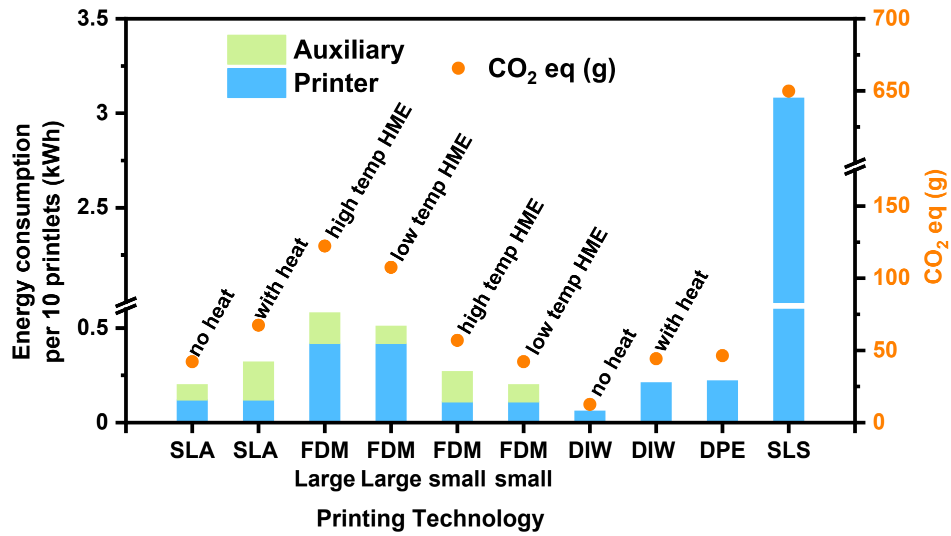

Fig. 2. Energy Consumption and calculated CO_2 emission data for fabricating 10 printlets. The energy consumption of ancillary equipment is also shown.

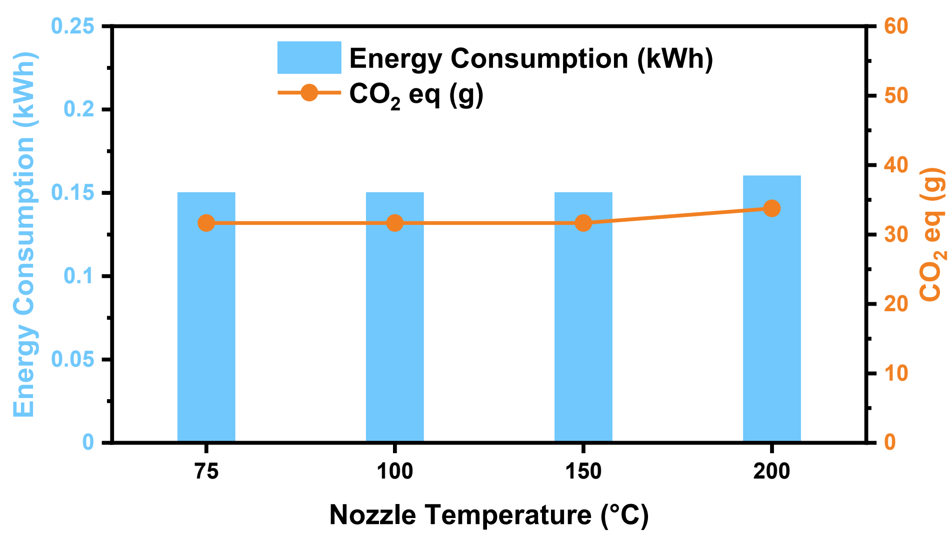

Fig. 3. Energy consumption and calculated CO_2 emission for the large FDM as a function of nozzle temperature.

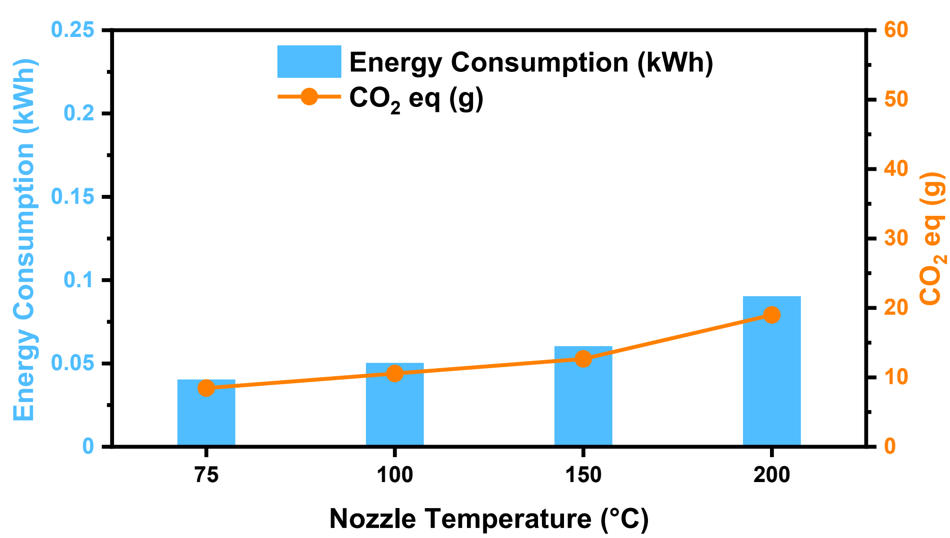

Fig. 4. Energy consumption and calculated CO_2 emission for the small FDM as a function of nozzle temperature.

lower spatial footprint than the FDM combined with HME. Like the FDM printers, the printing study in Section 3.2 was performed with a nozzle temperature of 200 °C, which required 8 min to reach. Also similar to the small FDM printer, lower printing temperatures in the DPE printer resulted in lower energy consumption. Reducing the temperature from 200 to 150 °C resulted in an 11.76% decrease in consumption, while a 29.41% decrease was seen when the nozzle temperature was decreased to 100 °C. Reducing the temperature to 75 °C reduced the energy consumption further by 41.18% (Fig. 5). Unlike, FDM, there are only limited studies using DPE, and the lowest nozzle temperature used during printing is 130 °C. Whether a pharmaceutical product could be printed at 75 °C is not known, but the present study has shown that if possible this could lead to further reductions in CO_2 emissions. The emission values ranged from 19.34 to 32.87 g CO_2 eq.

– DIW

DIW extrudes materials without heat provided the viscosity profile of the feedstock material is suitable, and is actuated using either a motor or compressed air. For the printer used in this work the actuation mechanism utilised compressed air and printlets were fabricated at either 30 or 65 °C. The energy consumption for low temperature printing was 26.19% less than printing at 65 °C (Fig. 6). The carbon emissions ranged from 32.87 g with at 30 °C to 48.5 g CO_2 (eq) when printing at 65 °C.

– SLS

SLS is a powder-based technology that uses a laser to sinter particulate matter into a monolithic structure. SLS uses powder as a feedstock; the powder is placed as a bed into the printing chamber and must be preheated to just below its sintering temperature. The laser then provides energy to exceed the sintering temperature threshold and allow the powder to fuse. Unlike the aforementioned material-extrusion technologies, therefore, a large volume must be heated and maintained at a high temperature. The analysis performed in Section 3.2 was at 180 °C, which is the maximum available. Reducing this by 50 and 100 °C resulted in 14.29% and 41.37% decreases in consumption respectively (Fig. 7). The carbon emissions ranged from 160.51 to 284.27 g CO_2 (eq).

– SLA

SLA uses light to cure photo-responsive polymers (also referred to as photopolymers). Some printers require heat to reduce photopolymer viscosity, but this feature is not found in all SLA printers. As mentioned above, heating may also be used in the post-processing stage, and section 3.2 clearly highlighted that avoiding heat resulted in lower CO_2 emissions.

The main printing parameter in SLA is exposure time, which governs the time the light source is switched on per layer. For the SLA printer, an increase in exposure time was found to increase the energy demand linearly. In section 3.2, the exposure time was 150 s per layer that resulted in an energy consumption of 0.12 kWh; decreasing the exposure time to 100 and 50 s per layer resulted in a linear consumption decrease to 0.08 and 0.04 kWh, respectively. Hence, if further reductions in carbon emission are needed, then consideration should be given to using formulations that rapidly cure.

4. Discussion

The growing demand for carbon neutral manufacturing is strongly driven by the need to mitigate the effect of CO_2 in our society. This includes the detrimental effect CO_2 imposes on health, which if not tackled, can lead to both direct and indirect health consequences (Malik et al., 2018), which in turn has been projected to place a heavy financial burden on healthcare institutes. Thus, there are both economic and health benefits to reducing CO_2 emissions. However, switching to carbon-neutral strategies should not come at the expense of inferior products and services. Therefore, there is a considerable desire to find strategies that can achieve both feats.

The present study demonstrates that 3D printers have the potential to fulfil their promise of delivering both enhanced and automated quality of service whilst being ‘environmentally affordable’. The energy consumption values reported herein, other than for SLS, are comparable to conventional tablet production by powder compaction (and for comparison, at least a magnitude smaller than that required for one computer tomography scan or magnetic resonance imaging, (Christiansen et al., 2016; Heye et al., 2020). These values are also comparatively low when measured against analytical techniques, such as HPLC (0.1–1.5 kWh per sample) and LCMS (>1.5 kWh per sample) (Kannaiah et al., 2021). It is also worth noting that tableting machines are operated over long periods of time, where the energy consumption per Kg decreases as productions are scaled up. (Hadinoto et al., 2022). Hence, further work is needed to assess whether the same applies to pharmaceutical 3D printers. Moreover, altering the design of the tablet in tableting machines requires additional tools, and this process is undoubtedly more CO_2 demanding than using a computer-aided software (CAD) software to easily change the design for a 3D printer. Such low energy demand suggests that 3D printers could be powered by renewable sources, such

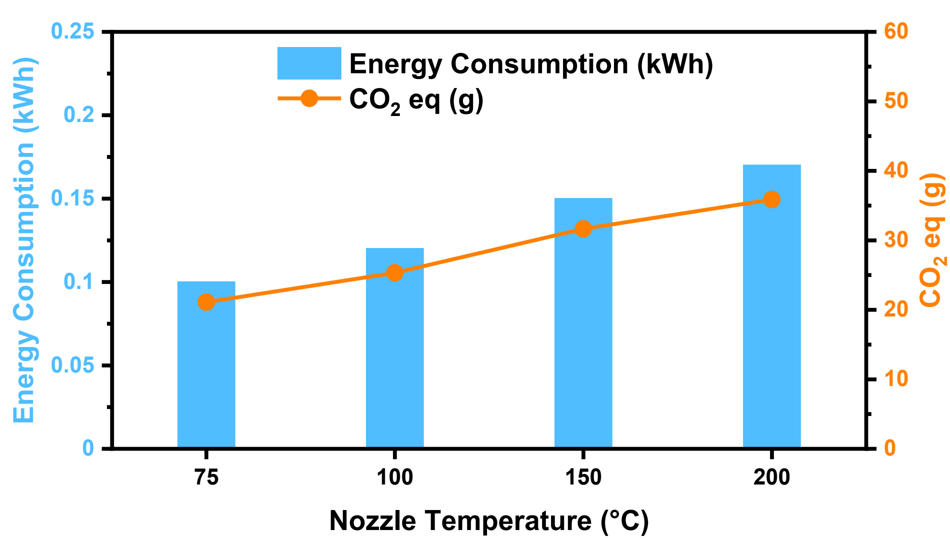

Fig. 5. Energy consumption and calculated CO_2 emission for the DPE as a function of nozzle temperature.

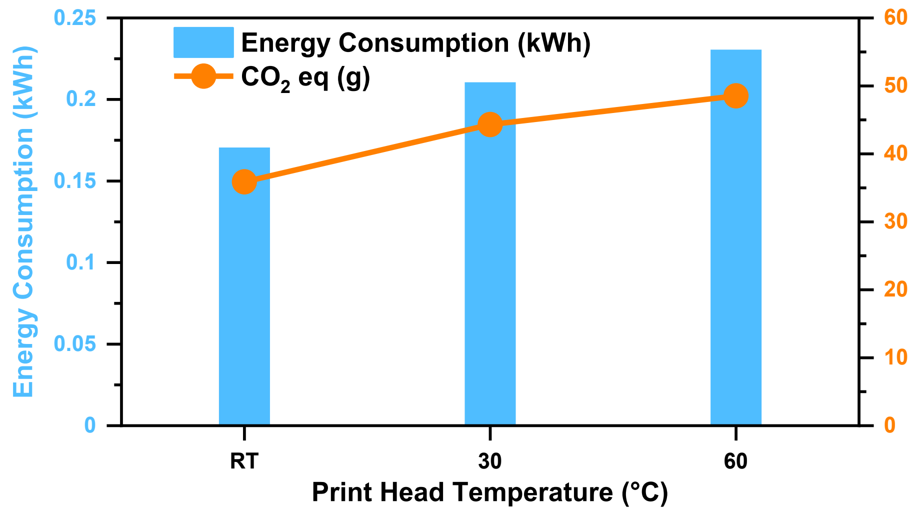

Fig. 6. Energy consumption and calculated CO emission for the DIW as a function of print heat temperature.

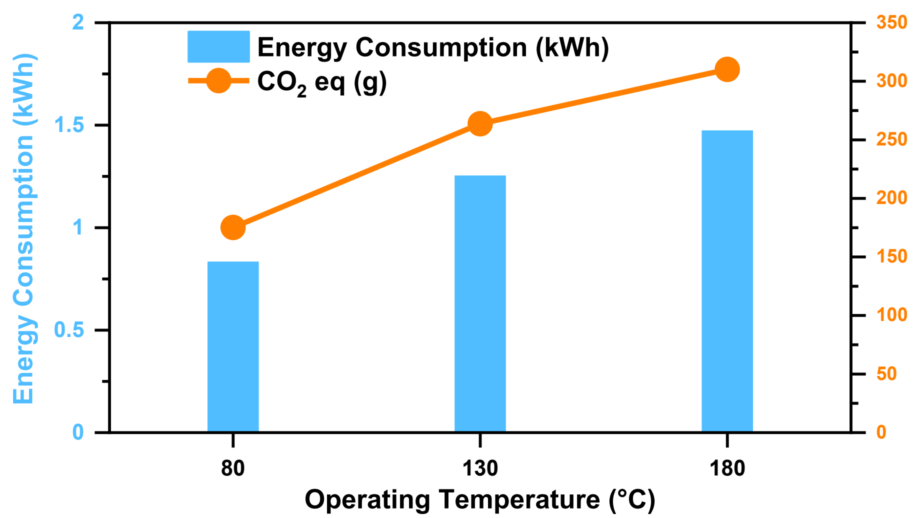

Fig. 7. Energy consumption and calculated CO_2 emission for the SLS as a function of chamber temperature.

as photovoltaic technologies (e.g. solar panels) to offset their CO_2 emission.

There are many other reasons why 3D printing could be considered as a mainstream replacement for powder compaction as the main manufacturing process of medicines. As a digitalised fabrication technology, 3D printers are powered by electricity, which is in contrast to other technologies that require oil (Coyle et al., 2021). Electricity is the easiest energy source to decarbonise and so 3D printing is then more amenable to being adopted by both industry and healthcare sectors (Jenkins et al., 2018). Further reduction in CO_2 emission can be made by reducing the operating temperature, although this may require a change in composition of the material being printed. For example, incorporating plasticisers allows for lower printing temperatures via FDM (Elbadawi et al., 2020). While changing the composition of a dosage form might alter its release profile, 3D printing allows for seamless design changes to compensate, such that both a lower operating temperature and the desired release profile can be achieved (Goyanes et al., 2015). It is worth highlighting that the operating temperature is just one of many parameters involved in 3D printing, and the effect of the other parameters warrants further research.

The study centred on the energy consumption of the 3D printing process, which is indeed one stage of the medicine life cycle. Other forms of emission can be directly emitted when processing polymers, which again may require a shift in formulation development, or carbon sequestration methods to minimise CO_2 emission. CO_2 emission can indeed arise from other sources from the supply chain, such as the production and subsequent transportation of raw pharmaceutical ingredients. Hence, these values will be needed to provide a holistic picture of CO_2 emission during medicine production.

5. Conclusion

There is a lack of knowledge associated with the environmental sustainability of 3D printed medicines, which may hinder the technology's adoption into both industry and healthcare settings. This study explored the energy required by 3D printers to fabricate solid dosage forms, and allowed an approximation of the CO_2 emission generated. On standby, the printers consumed between 0.03 and 0.17 kWh, whereas between 0.06 and 3.08 kWh was consumed for producing ten printlets. The study showed 3D printers using elevated temperatures had a higher consumption demand; reducing the printing temperature can lead to a significant reduction in energy demand, with reductions of 5.88% to 33.33% being achieved by printing 50 °C lower, depending on the printing technology. Hence, one strategy to becoming more environmentally efficient is to reduce the operating temperature.

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.

Data availability

Data will be made available on request.

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