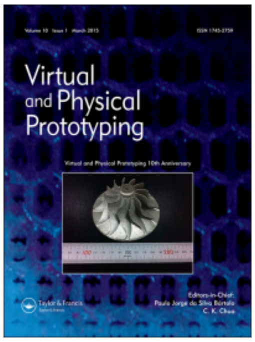

Virtual and Physical Prototyping

ISSN: 1745-2759 (Print) 1745-2767 (Online) Journal homepage: www.tandfonline.com/journals/nvpp20

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To cite this article: Jinlong Su, Wei Long Ng, Jia An, Wai Yee Yeong, Chee Kai Chua & Swee Leong Sing (2024) Achieving sustainability by additive manufacturing: a state-of-the-art review and perspectives, Virtual and Physical Prototyping, 19:1, e2438899, DOI: 10.1080/17452759.2024.2438899

To link to this article: https://doi.org/10.1080/17452759.2024.2438899

VIRTUAL AND PHYSICAL PROTOTYPING
2024, VOL. 19, NO. 1, e2438899 (34 pages)
https://doi.org/10.1080/17452759.2024.2438899

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REVIEW ARTICLE

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Achieving sustainability by additive manufacturing: a state-of-the-art review and perspectives

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ABSTRACT
As global awareness of resource scarcity and environmental concerns grows, sustainable manufacturing practices have become imperative. Additive manufacturing (AM), with its high material efficiency and design flexibility, presents a promising pathway toward sustainable industrial transformation. This review explores AM's role in sustainability across its lifecycle: design for AM, in AM, and after AM. In the design for AM phase, strategies such as topology optimisation, part consolidation, and cellular structures reduce material usage and enhance durability. During AM, in-situ process monitoring and closed-loop control improve process reliability, reducing energy consumption and failure rates. Meanwhile, the adoption of sustainable materials—metals, polymers, concretes, and biomaterials—further strengthens AM's potential to advance sustainability. After AM, applications such as repair, remanufacturing, and recycling extend product lifecycles and reduce environmental impact, aligning with circular economy principles. Future perspectives include the integration of artificial intelligence for in-process control and sustainable material development, along with regulatory and circular economy frameworks critical to sustainable AM deployment. Lastly, emerging research trends in advancing sustainability through AM are reviewed. Overall, this review provides a roadmap for academia and industry, offering strategies and insights to maximise AM's contribution to a more sustainable and responsible manufacturing future.

ARTICLE HISTORY
Received 17 November 2024
Accepted 2 December 2024

KEYWORDS
Additive manufacturing; 3D printing; sustainability; life cycle assessment; artificial intelligence

1. Introduction

With increasing global resource scarcity and heightened environmental awareness, the manufacturing industry faces unprecedented pressure to transform. Traditional manufacturing methods, such as casting, powder metallurgy and machining, often have low efficiency in material utilisation and high energy consumption, resulting in significant resource waste and environmental pollution. These challenges underscore the urgent need for green manufacturing practices to mitigate the environmental impact of industrial processes [1]. Addressing global challenges like climate change and resource depletion requires transformative innovation in manufacturing technology, fostering advancements that align with sustainability goals.

In this context, additive manufacturing (AM), known as 3D printing, has emerged as a pivotal technology in this regard due to its potential to reduce material waste, enable flexible designs, and offer unparalleled customisation capabilities [2–4]. As shown in Figure 1, the research trends in achieving sustainability through AM have grown exponentially over the years, with over 900 publications expected by 2025. The geographical distribution of these publications highlights the United States as the largest contributor (33.2%), followed by India (12.6%) and Italy (10.7%). This trend reflects the increasing global interest in exploring AM's role in addressing sustainability challenges, further emphasising its importance as a transformative technology.

According to the American Society for Testing and Materials (ASTM) standard F2792-12a, AM techniques are classified into the following categories: material extrusion, binder jetting, material jetting, vat photopolymerization, powder bed fusion, sheet lamination and directed energy deposition [5,6]. The schematic illustration of theses AM techniques are presented in Figure 2 [7]. Unlike traditional manufacturing methods, AM constructs objects layer by layer, enabling complex

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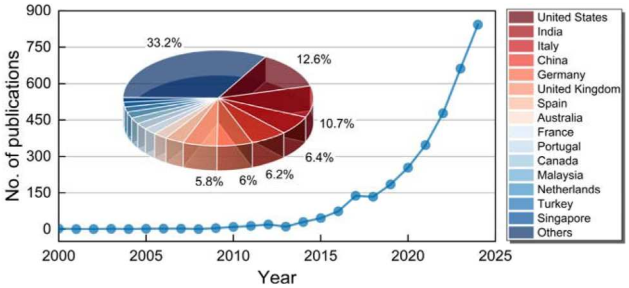

Figure 1. Research trends in achieving sustainability by additive manufacturing (data sourced from Scopus using the keywords 'additive manufacturing' and 'sustainable').

geometric structures while significantly reducing energy consumption and enhancing material efficiency [8]. In recent years, AM has been increasingly adopted in industries such as aerospace, healthcare, and automotive due to its efficient material allocation and customisation potential [9,10].

Assessing the sustainability of AM processes requires a comprehensive understanding of their environmental impacts, which can be effectively measured using key metrics such as carbon footprint [11], material recyclability rates [12], and energy consumption [13]. Figure 3 illustrates the benefits of AM in achieving sustainability. Notably, AM not only demonstrates sustainability benefits during the AM fabrication (materials and processes) but also spans across design for AM and applications after AM [14,15]. In the design for AM phase, AM allows for more flexible geometric design capabilities, enabling the creation of optimised designs that minimise material waste and energy consumption. Furthermore, the ability to design complex parts as a single piece eliminates the need for assembly, further reducing resource use and manufacturing steps. In the materials aspect of AM, the technology significantly improves material utilisation rates. Waste materials, such as machining chips and swarf, can be recycled into AM-grade feedstock, reducing waste and promoting circular material usage. Additionally, AM enhances material value by enabling improved performance through innovative material development. In the AM processes, AM facilitates the mass production of customised products, offering improved resource efficiency and enabling product variations without requiring additional tooling or infrastructure investments. This flexibility supports sustainable manufacturing practices by reducing unnecessary resource consumption. Finally, in applications after AM, the benefits continue with reduced storage requirements and increased material value, as parts are produced on demand. AM also minimises factory operation time and transportation needs by producing parts closer to the point of use. Moreover, the ability to produce lightweight components lowers fuel costs and carbon emissions, making it particularly advantageous for industries such as aerospace and automotive. Overall, the sustainability benefits of AM span the entire lifecycle of manufacturing, from design to material use, fabrication, and application, making it a transformative approach for achieving sustainable production.

Despite the considerable progress in AM technologies, a systematic review addressing their sustainability across all stages—design for AM, in AM, and after AM—remains lacking [16]. Most existing studies focus on isolated aspects, such as material efficiency during AM or energy savings in specific processes, without offering a holistic perspective. To this end, this review seeks to address this gap by exploring the comprehensive potential of AM in achieving sustainability. Additionally,

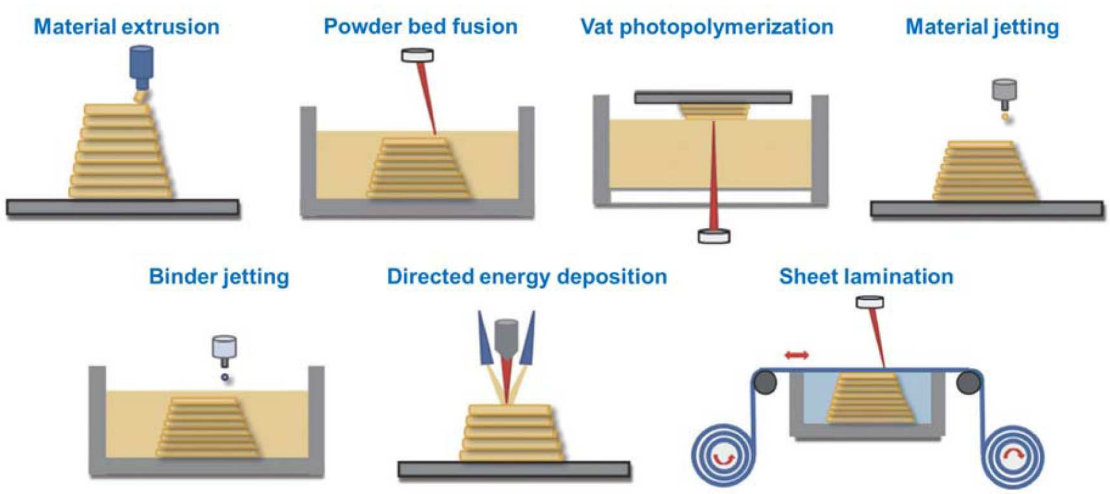

Figure 2. Schematic illustration of AM techniques. Reprinted from [6] under the Creative Commons CC BY-NC-ND 4.0 license.

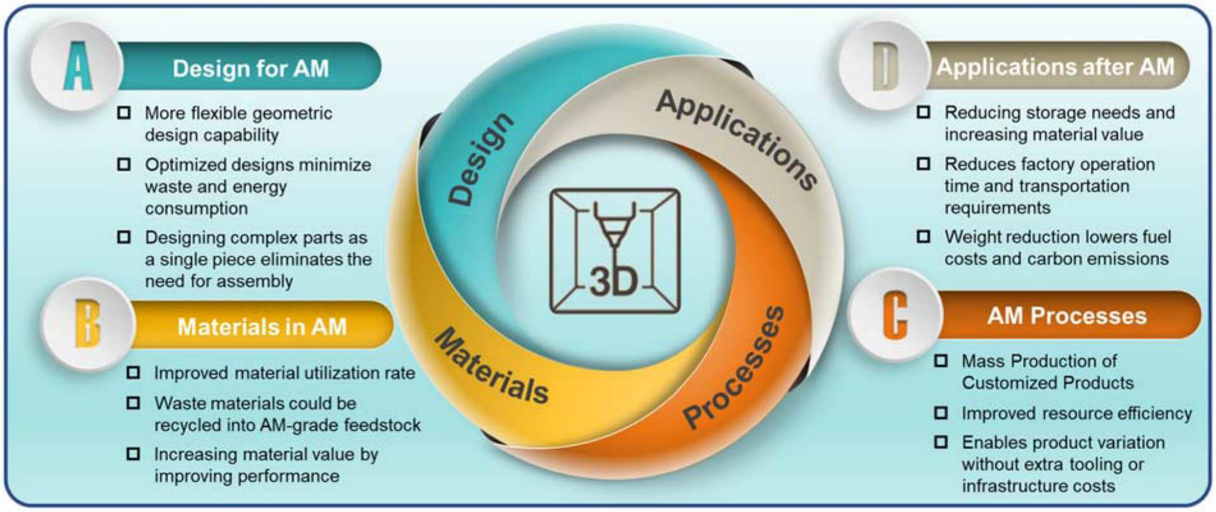

Figure 3. The benefits of AM in achieving sustainability.

emerging technologies, such as machine learning, present promising opportunities for enhancing the sustainability impact of AM [17–19]. By systematically reviewing the current advancements and identifying areas for future exploration, this paper provides a comprehensive guide for both academia and industry. It highlights not only the current achievements in achieving sustainability by AM but also key research directions to fully unlock its potential as an environmentally responsible manufacturing solution.

Overall, this review aims to systematically explore the potential of AM in achieving sustainability, focusing on its application and development across all stages: design for AM, AM itself, and post-AM. By reviewing recent advancements in reducing material waste, enhancing resource efficiency, and minimising environmental impact through AM, this paper offers insights and guidance for industry practitioners and policymakers in adopting AM technologies for sustainable manufacturing. By identifying state-of-the-art progress and future directions, this paper also outlines a roadmap for leveraging AM to achieve sustainability goals, addressing sustainable materials development, innovations in AM processes, and the evolving regulatory and economic frameworks driving environmentally conscious practices.

2. Sustainability in design for AM

Previously, there are some economic and cost evaluations on AM, but not as explicit and broad as those in sustainability evaluation; also, there is a lack of evaluation of environmental sustainability on AM [20,21]. Sustainability of AM is usually studied in the form of case studies with reference to conventional manufacturing. The goal is to supply evidence to support the hypothesis that AM is more sustainable compared to conventional methods in terms of economic, environmental, and societal impact [22,23]. A recent survey with 16 Chinese manufacturing companies that have adopted AM offers some insight into the sustainability benefits of AM on an industrial scale [24], demonstrating its positive impact in practice. For instance, life cycle assessments (LCA) conducted in the context of this survey revealed significant reductions in energy consumption and material waste for low-volume production compared to traditional manufacturing methods. However, evaluating sustainability benefits of AM is just the beginning, how to contribute better or how to optimise the sustainability benefits remains unanswered. Therefore, sustainability of design for additive manufacturing (DfAM) becomes an important subject of study. In general, there are two types of investigation in sustainability of DfAM: (1) to understand the sustainability potential of DfAM, in which a sustainability analysis such as LCA is usually conducted during or after AM; (2) to systematically implement sustainability design methodology in DfAM. The first has laid down foundations for industry to confidently adopt and integrate AM in the manufacturing process chain, while the second represents the future research development from both academy and industry.

To put together sustainability and DfAM, one approach is to differentiate it from DfAM by establishing a new research area, since the integration or blending of sustainability design and DfAM represents a totally new design concept for AM products. Another approach is to redefine DfAM by extending the scope to include sustainability design. Alfaify et al. classified DfAM strategies into seven categories: cellular structures, consolidation and assembly of parts, materials, support structures, build orientation, part complexity, and product sustainability [25]. This classification combines the two types of investigation mentioned above and sustainability design is proposed as a component of future DfAM. Nevertheless, the efforts to integrate sustainability with DfAM will evolve over time and it may not be impossible for this interdisciplinary field to grow stronger in future and stand alone.

Cellular structures, especially lattice structures, are usually designed to replace traditional bulks for mass reduction and lightweight applications [26]. It is generally believed that when less materials are used greater sustainability is achieved. However, a recent study found that lattice design could negatively impact sustainability, because complex structures take longer time to manufacture and consume more electrical energy [27]. It is concluded that there is a trade-off between lattice-driven mass reduction and productivity and a balance must be reached. For cellular structures, studies have shown that increasing the infill density in fused deposition modelling (FDM) leads to higher CO_2 emissions, while parameters like infill pattern and layer thickness have minimal impact on environmental performance [28]. This is likely because higher infill density takes longer to manufacture. Therefore, depending on the angle and spectrum of sustainability analysis, there can be both positive and negative impacts on sustainability, either should not be missing to avoid biased sustainability analysis.

Part consolidation and assembly design is another important DfAM strategy. Through part consolidation, one can reduce weight and size, minimise or eliminate assembly operation, improve overall performance, and prolong service life [29,30]. It is reported by Boeing that AM consolidated thousands of components into single parts, eliminating the need for thousands of secondary fasteners (e.g. bolts) [31]. This process significantly lowered the carbon emissions associated with fabricating, warehousing, transporting, inspecting, testing, and assembling these fasteners. However, one study pointed out that part consolidation requires AM to completely or partially replace conventional manufacturing, when this happens, the toxicity problems associated with the AM method (e.g. binder jetting) could increase accordingly, presenting some negative impact on sustainability [32]. An LCA study revealed that binder-jetting AM reduces energy consumption to 49.3 MJ for an optimised part, compared to 118.2 MJ for CNC machining, achieving a 58% reduction [33]. CO_2 emissions are also halved, with AM producing 49.3 kg CO_2-equivalent versus 118.2 kg for CNC machining. However, human toxicity impacts, measured in Dichlorobenzene (DCB) equivalents, are higher for AM at 44.1 kg compared to 29.5 kg for CNC machining, due to the use of bronze in the binder-jetting AM process. These impacts can be mitigated by leveraging AM's design optimisation capabilities to reduce weight and exploring alternative materials. Again, this highlights the necessity and importance of incorporating sustainability goals into DfAM.

Part complexity is usually coupled with topology optimisation to improve material efficiency, i.e. using less materials to achieve greater and better functions. There are studies evaluating the sustainability of topology optimised AM products [34,35], and positive environmental impacts have been reported. In the automotive industry, Priarone et al. [36] reported that a bracket originally made of iron was redesigned using AM, achieving an impressive 69% weight reduction through topology optimisation. Furthermore, Akkurt et al. [37] reported that a drone chassis was optimised using advanced topology optimisation techniques, resulting in approximately 78% mass reduction. These weight reductions could contribute significantly to lifetime CO_2 emissions savings during service. These applications highlight the transformative potential of AM in contributing to sustainability across industries by reducing energy consumption and material waste. However, like cellular structures, part complexity might be correlated to productivity issues if topology optimization optimises material efficiency but compromises process efficiency, which could lead to potential negative impacts on sustainability.

Other DfAM strategies such as build orientation optimisation and support structure design could also produce some impacts on sustainability. For example, when using stereolithography to manufacture a part, build orientation affects the quantity and volume of support needed, as well as the overall printing time, which are related to LCA indicators [38]. Optimising the build orientation could minimise the environmental impact by generating less waste and consuming less electrical energy. Another study involving the laser powder bed fusion (LPBF) process also demonstrated the potential impact of support and build orientation on sustainability [39]. Even support alone, in the case of extrusion AM, the volume of support material and the time needed for its removal (dissolution in solution) have significant environmental impact [40].

Sustainability analysis can be conducted not only during or after AM but also in the DfAM stage. Wang et al. introduced the approach of EcoDfAM, which stands for Eco-Design for Additive Manufacturing [41]. It is a novel cross-subject field of Design, Sustainability and Additive Manufacturing. Their method can capture implicit knowledge and correlations among AM, Design, and Sustainability domains through the Material-Process-Structure-ecoProperty (MPSeP) relationships. The sustainability information is pre-defined in DfAM. A case study on a hydraulic manifold showcased its effectiveness in retrieving essential data related to carbon emission and cost, eco-parameters used in DfAM. Another approach is including sustainability in topology optimisation of AM products. For example, analyses of intermediate topology results allow the estimation of support structures and build direction, from which LCA model can calculate the sustainability indicators for design considerations [42]. Besides, the use of machine learning can also power data-driven, automated sustainability analysis of DfAM [43]. Therefore, when integrating sustainability design with DfAM, topology optimisation and artificial intelligence are enabling tools for faster and quality design of sustainable AM products [44].

Taken together, the abovementioned works have shown the impact of DfAM on sustainability, (summarised in Table 1). Although most impacts are positive due to the synergy between DfAM goals and sustainability goals, LCA results have occasionally identified potential negative impacts, such as higher energy use or emissions, which deserve attention to achieve balanced sustainability outcomes. For practical adoption of AM, a balanced view on the impact on sustainability is necessary. Moreover, integrating sustainability design with DfAM in a single design process can meet both goals simultaneously, representing a future research direction for DfAM. Furthermore, the potential of technologies relevant to DfAM such as topology optimisation and artificial intelligence require further exploration to enhance the integration.

3. Sustainability in AM

3.1. AM in-process control

Traditional manufacturing techniques, such as casting and forging, often result in microstructural inhomogeneity and internal defects when producing large-format and/or complex-shaped parts, leading to substantial material waste. However, in AM, these challenges can be mitigated effectively through in-process control due to its layer-by-layer manufacturing nature, reducing printing failure rate and material wastage [45]. In AM in-process control, two typical stages are shown in Figure 4: in-situ process monitoring and adaptive quality enhancement [46]. With in-situ process monitoring, anomalies and defects such as deformation, voids, or other imperfections can be detected in the early stage during AM [47]. Then, closed-loop feedback control (e.g. adjusting laser power or scan speed [48]) or in-process defect correction (e.g. hybrid additive-substrative manufacturing [49]) can be performed to achieve zero-defect and highly-accurate parts fabrication, thus reducing material waste and build failure rate [50].

Figure 4(a) presents a schematic illustration of typical in-situ process monitoring techniques used in AM, including a coaxial CCD camera for capturing melt pool visual images, a microphone for recording acoustic signals, and an infrared thermal camera for monitoring the temperature field. Monitoring techniques, such as optical-based and acoustic-based sensing, facilitate early defect detection, allowing for timely interventions that minimise material wastage and reduce failed prints, optimising resource use. Gobert et al. [52] reported that optical monitoring systems equipped with high-resolution cameras can detect surface irregularities in real-

Table 1. Understanding the impact of DfAM on sustainability.

DfAM strategy	AM process and material	Case study	Impact on Sustainability	Ref
Cellular structure	Fused deposition modeling of ABS and PLA	Infill density, the infill pattern (gyroid, triangle and grid) and the layer thickness	Increasing infill density led to higher CO_2 emission, while layer thickness and infill pattern does not affect CO_2 emissions.	[28]
Cellular structure	LPBF of AlSi10Mg alloy	the lower arm of a MacPherson front strut suspension system (automotive component)	Latice designs reduced weight but also affect productivity and consume more energy, hence negatively impact sustainability	[27]
Part consolidation and assembly	LPBF of stainless steel	A throttle pedal of a passenger vehicle	More environment friendly when part lifespan is increased by 200% or the weight savings exceed 30%	[30]
Part consolidation and assembly	Binder jetting of polymer powder	Floor attachment in a train	Consolidated design reduced energy consumption and environmental impact, but increased health toxicity problems related to the BJ process	[32]
Part complexity	LPBF of aluminum alloy	Rocker arm (automotive component)	Weight reduction of 5g by topology optimization resulted in 21.31% less environmental damage	[35]
Part complexity	N.A.	Damping bracket (automotive component)	AM of topology optimized shapes uses less material and reduces production time, hence has sustainability benefits compared to machining and casting processes	[34]
Build orientation and support	Stereolithography of epoxy resin	3D Benchy torture test model	There existed an optimal orientation in terms of material usage and electrical energy consumption	[38]
Product sustainability	LPBF of stainless steel	Hydraulic manifold	EcoDfAM to pre-defined sustainability goals: 40 kg CO_2-Eq carbon emission; USD $30 cost	[41]

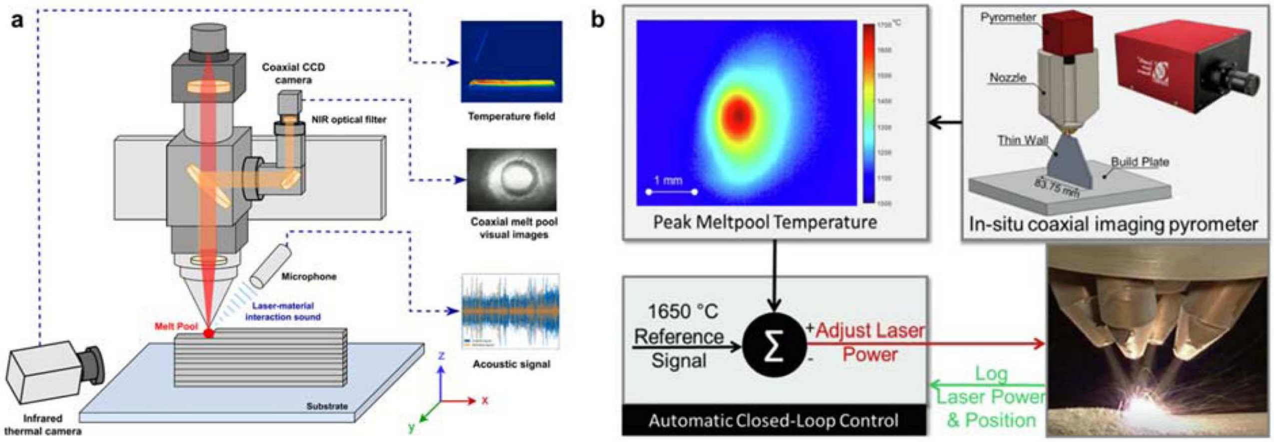

Figure 4. Schematic illustrations of AM in-process control: (a) Typical in-situ process monitoring techniques for AM, including an infrared thermal camera for capturing the temperature field, a microphone for recording acoustic signals, and a coaxial charge-coupled device (CCD) camera for collecting visual images of the melt pool [51]. Reprinted with permission from Elsevier @ 2023. (b) Closed-loop control of melt pool temperature in AM to mitigate porosity defects and promote uniform microstructure [48]. Reprinted from [48] under the Creative Commons CC BY-NC-ND license.

time, significantly reducing the occurrence of failed prints by allowing for immediate corrective actions [53]. Besides, Chen et al. [54] demonstrated that acoustic sensors have been effectively used to detect anomalies, such as cracks and porosities, by capturing the noise generated during the printing process, thus preventing the continuation of defective prints. Additionally, Hocine et al. [55] reported that the application of operando X-ray monitoring can identify internal defects that are not visible to external scanning methods, ensuring the integrity of critical components such as aerospace parts. Besides, the use of real-time X-ray imaging enables the detection of structural failures within layers during the manufacturing process, which helps in producing more durable and reliable components, minimising the likelihood of future failures and replacements [56,57]. These examples underline the vital role of in-situ process monitoring in AM. The integration of advanced sensors to monitor AM process could reduce the build failure rate and improve the part quality, thereby achieving sustainability by reducing material and energy consumption.

Once the anomalies are detected by in-process monitoring, the adaptive quality enhancement approaches can be performed to enhance process consistency and part quality, leading to increased energy efficiency by reducing trial-and-errors [58]. For instance, Smoqi et al. [48] demonstrated that a closed-loop control system, using real-time melt pool temperature feedback to adjust laser power, effectively reduces flaws in laser-directed energy deposition (LDED) of 316L, as shown in Figure 4(b). By maintaining the melt pool temperature within a set range (1650 ± 50 °C), the system minimised porosity variation and ensured a uniform microstructure. Besides, Bernauer et al. [59] demonstrated the effectiveness of a segmentation-based closed-loop control system to ensure dimensional accuracy and stability in wire-feed LDED. By dividing the weld beads into segments and adjusting the wire feed rate for each segment, the control system maintained a constant layer height even under disturbances. Compared to open-loop processing, these closed-loop control approaches achieve more consistent part quality, underscoring the importance of in-process control in improving process reliability and minimising post-processing requirements.

Additionally, note that AM with auxiliary process (e.g. auxiliary heating) could also be favourable for achieving sustainability [60,61]. For instance, Fu et al. [62] investigate the auxiliary hot-wire process for wire-are additive manufacturing (WAAM) of 2024 Al alloy. By preheating the wire feedstock, the deposition rate can be increased by three times (from 86 to 301 cm^3/h), while reducing porosity in the fabricated part as well. Similarly, Sang et al. [63] proposed that auxiliary hot-wire process not only improve deposition rate, but improve the surface roughness and macroscopic profile accuracy as well in LDE due to the more stable melt pool involved. Overall, the integration of auxiliary heating into AM provide new opportunities to improve both build efficiency and profile accuracy, leading to reduced costs while minimising the need for post-processing treatment (e.g. edge trimming) [60]. In addition to auxiliary heating, other auxiliary processes—such as magnetic-field-assisted AM, ultrasonic-vibration-assisted AM, and deformation-assisted AM—also offer new opportunities for achieving sustainability by improving part quality, process reliability, build efficiency, and/or reducing costs. These approaches, known as field-assisted AM (FAAM), are thoroughly reviewed in Ref. [60] and thus will not be discussed here in detail.

3.2. Material utilisation

3.2.1. Metals

Metal AM plays a crucial role in achieving sustainability by enhancing material efficiency, reducing energy consumption, and minimising greenhouse gas emissions. Unlike conventional manufacturing (CM), metal AM significantly lowers material waste by utilising near-net-shape production, reducing the 'buy-to-fly' ratio to as low as 1.5 compared to ratios as high as 30 in CM [64]. AM's capability to produce lightweight components with optimised geometries directly contributes to fuel savings in applications such as the aerospace industry, where lighter components reduce operational energy demand. As shown in Figure 5, the cradle-to-gate primary energy savings achieved by metal AM components are significant, demonstrating its potential to revolutionise manufacturing processes with substantial environmental benefits. By integrating AM into industrial workflows, industries can move closer to meeting global energy and emissions reduction goals while achieving economic efficiency.

For metal AM, PBF (including LPBF and electron beam melting (EBM)) and DED (including LDED and WAAM) are commonly used [65]. Among these techniques, the LPBF process offers the highest dimensional resolution, making it particularly suitable for fabricating complex-shaped parts, such as those with internal cooling channels [60]. In contrast, LDED and WAAM achieve significantly higher deposition rates compared to LPBF and EBM. In terms of material efficiency, powder-based AM techniques (LPBF, EBM, powder-feed LDED) generally exhibit lower efficiency than wire-feed AM techniques (wire-feed LDED, WAAM). For wire-feed AM techniques (wire-feed LDED, WAAM), material efficiency can reach nearly 100% with sufficiently optimised process parameters. In contrast, powder-feed AM suffers from lower material utilisation because not all powders can be captured into the melt pool. According to Zhang et al. [66], the material utilisation rate for 316L steel in powder-feed LDED is approximately 50% to 78.3%. For PBF techniques such as LPBF and EBM, although the powder can be recycled after printing, degradation in powder quality (e.g. sphericity, composition) is inevitable. Furthermore, the cost of raw wire is significantly lower than that of raw powder because wire production processes are simpler and more cost-effective. The material efficiency of AM-processed metallic materials follows the order: WAAM > wire-feed LDED > EBM >

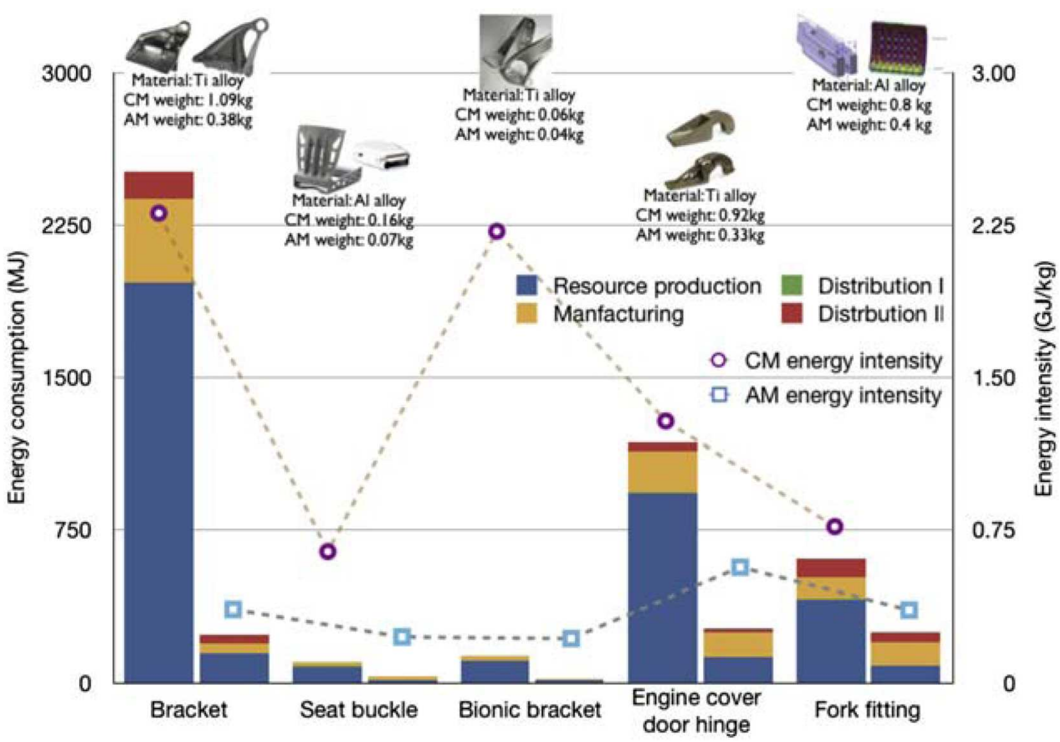

Figure 5. Comparison of cradle-to-gate primary energy consumption in conventional manufacturing (CM) and additive manufacturing (AM) [64]. Reprinted with permission from Elsevier @ 2016.

LPBF > powder-feed LDED, while energy consumption ranks in the reverse order: LPBF < EBM < powder-feed LDED < wire-feed LDED < WAAM [60]. Anne et al. [67] performed an LCA comparing WAAM with green sand casting and CNC milling for stainless steel 308L. They found that WAAM has a total ReCiPe endpoint impact of 1.832 Pt per kilogram, comparable to green sand casting at 1.892 Pt and significantly lower than CNC milling at 2.825 Pt when the material utilisation fraction is 0.5. WAAM's advantages include high material efficiency (98.9%) and the ability to reduce environmental impact linearly through topology optimisation, making it a more sustainable option for manufacturing complex shapes. Overall, this indicates that WAAM and wire-feed LDED are more favourable for achieving sustainability due to their relatively low cost, high material efficiency, and high deposition rates, making them particularly suitable for fabricating large-format parts or components [68].

In conventional metal manufacturing, significant amounts of machining chips and swarf are generated during processes such as turning, milling, drilling, and grinding [1]. As much as 90% of the raw material may become scrap during these steps, resulting in substantial waste and a low material utilisation rate [69,70]. Thankfully, this waste could potentially be recycled and reused as feedstock for AM [71,72]. For instance, Beck et al. [73] introduced a novel sustainable friction stir AM process that can utilise waste machine chips as feedstock, as shown in Figure 6. The forming principle involves consolidating and bonding metal chips into a dense solid structure through high-temperature friction stir AM process. It is reported that the strength and fatigue performance of materials fabricated from machine chips are comparable to those made from solid bar feedstock. This sustainable AM technique which directly recycles waste materials, holds great promise for advancing sustainability. Although chips and swarf often become highly contaminated and oxidised during machining, parts fabricated from these recycled materials could still be suitable for applications with relatively lower property requirements.

However, for most of commonly used metal AM techniques, irregularly shaped chips and swarf may not be suitable as feedstock. Instead of using waste materials directly, an alternative approach is to convert these irregular-shaped materials into AM-compatible feedstock through processing/deformation. A typical example is demonstrated by Smythe et al. [74], where continuous extrusion was used to consolidate reused alloy powder and machining swarf waste into wire. These wires can then be utilised in wire-feed AM techniques, such as wire-feed L-DED or WAAM. This technology has the potential in transitioning to more sustainable supply chains by reducing the demand for virgin raw materials. Additionally, Khan et al. [75] proposed that these waste chips could be compressed into a substrate or support structure for AM, which would not only save raw material but also simplify part removal.

In addition to recycling waste materials, the design of sustainable low-cost simplified alloys for AM also

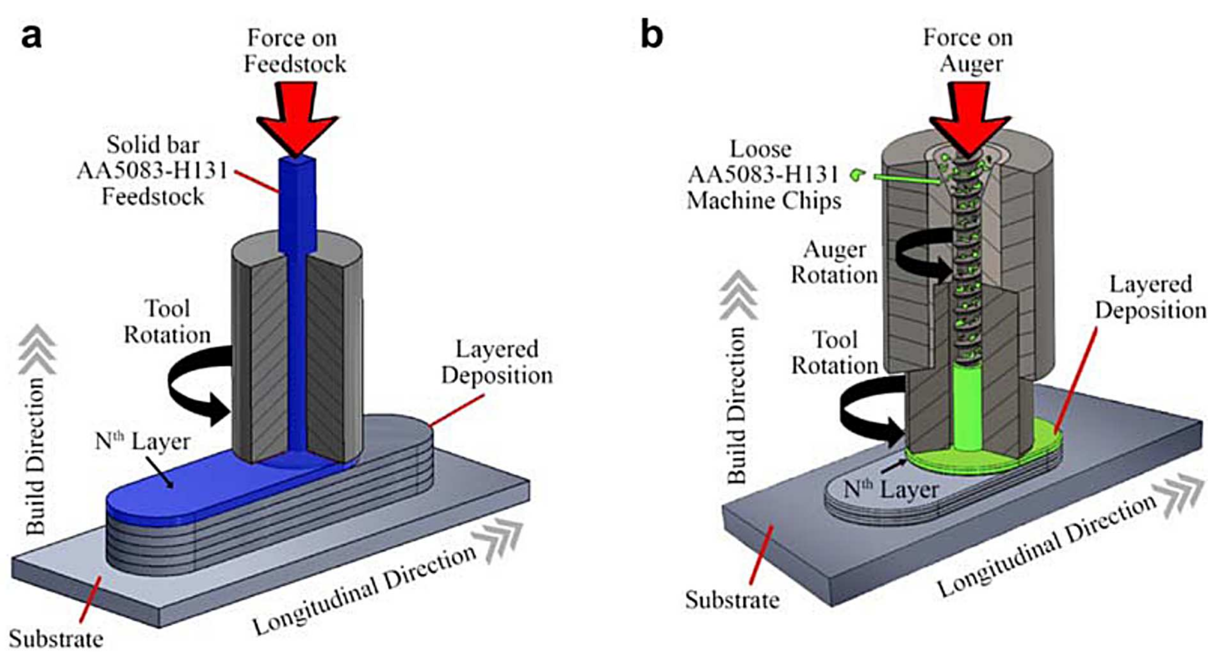

Figure 6. Schematic illustrations of two friction-stir AM processes using (a) solid bar feedstock, (b) feedstock made from waste machine chips. Reprinted from [73] under the Creative Commons CC BY-ND license.

contributes to achieving sustainability. For instance, titanium (Ti) alloys are sought-after high-performance materials for aerospace and automotive applications due to their superior specific strength, great fatigue performance and excellent corrosion resistance [76–78]. However, the high cost of Ti alloy raw powder limits their broader applications in AM [79]. To address this material cost challenge, Song et al. [80] proposed the combination of oxygen (O) and iron (Fe) as stabilizing and strengthening elements for α–β titanium alloys, and the microstructure of the Ti-O-Fe alloys fabricated by LDED are shown in Figure 7. Through integrating alloy design with AM processes, it is demonstrated that the Ti-O-Fe alloys could exhibit outstanding tensile properties. For instance, the Ti-0.14O-3.23Fe alloy showed a tensile elongation (ε_f) of 9.0 ± 0.5% and an ultimate tensile strength (UTS) of 1,034 ± 9 MPa, while the Ti-0.34O-3.25Fe alloy demonstrated ε_f of 21.9 ± 2.2% and UTS of 1,194 ± 8 MPa. This integration not only enabled the development of strong and ductile α–β Ti-O-Fe alloys but also offered a pathway for using off-grade sponge Ti, a typically discarded industrial by-product, thereby potentially reducing the carbon footprint of the energy-intensive production of sponge Ti. Meanwhile, incorporating oxygen as an element indicates that this low-cost Ti-O-Fe alloy has a much higher oxygen tolerance compared to conventional Ti alloys. The enhanced oxygen tolerance allows for extended reuse cycles, slows down powder aging during AM and further reduces costs [81]. Similarly, Tan et al. [82] demonstrated that plain carbon steels can be effectively utilised in AM to achieve high-performance martensitic and bainitic microstructures without requiring complex alloying or additional heat treatments. The 3D-printed plain carbon steels exhibit mechanical properties comparable to, or even surpassing, those of ultra-high-strength alloy steels and maraging steels, offering exceptional strength, ductility, and impact toughness. This finding challenges the conventional notion that such high performance necessitates complex alloy compositions.

Notably, in conventional metal manufacturing, heat treatment is typically required, which is both time-consuming and costly [83]. Besides, even for most commercial alloys prepared by AM, post-heat treatment remains necessary [84–87]. Take the commercial 18Ni300 maraging steel as an example, aging treatment or solution-aging treatment are essential to induce high-density precipitation, so as to achieve superior strength [88,89]. This is because these commercial materials were not originally designed for AM, and their development did not account for the intrinsic thermal cycling characteristics of AM in the alloy design stage [90]. As a result, developing novel heat-treatment free alloys dedicated to AM presents a highly promising pathway to enhance sustainability. For instance, Kürnsteiner et al. [91] have successfully designed a novel heat-treatment free Fe-19Ni-5Ti (wt%) maraging steel tailored for AM. By leveraging the intrinsic thermal cycling of LDED, the in-situ precipitation of high-density η-Ni_3Ti precipitates are induced, significantly strengthening the alloy. Thanks to this in-situ heat treatment effect, the LDED-built Fe-19Ni-5Ti (wt%) maraging steel achieves a tensile strength of 1300 MPa and an elongation of 10%. The similar in-situ precipitation phenomenon of AM has also been reported in a Mg-15Gd-1Al-0.4Zr alloy [92] and an Al-1Sc-0.4Zr (wt%) alloy [93]. By leveraging the in-situ thermal cycling nature of AM, such alloys eliminate the need for post-heat treatment, significantly reducing manufacturing lead time and accelerating production workflows.

Lastly, for metal PBF techniques (LPBF and EBM), improving powder reusability is crucial for reducing raw material costs due to the high expense of metal powder. However, due to the interaction between heat source and powder, the quality of the raw powder, including composition and morphology, inevitably degrades with increasing reuse cycles [94]. Specifically, the particle size distribution narrows, and the powder morphology becomes irregular after several reuse cycles [95,96]. Tang et al. [97] reported that for the Ti-6Al-4V alloy, oxygen content progressively increased with increasing reuse cycles, while the Al and V content remained relatively stable, with only a slight decrease (Figure 8(a)). To extend reuse cycles, adding a portion of virgin powder and thoroughly blending could be a feasible approach to prolong the powder's reusability. (Figure 8(b)). Besides, it has been reported that the tensile strength of Ti64 alloy fabricated by AM increases with increasing reuse cycles (Figure 8(c)) [97–100], likely due to oxygen uptake during reuse. In addition, two typical powder refreshing strategies to enhance reusability are illustrated in Figure 8(d) [94]. Compared to the single-batch approach, the frequent refreshing (top up) strategy involves rejuvenating used powder by blending it with virgin powder after a defined number of build cycles. This method can reduce powder waste, extend the usable life of the powder, and lower costs. However, proper blending is essential to avoid inhomogeneity and to maintain traceability, which is particularly critical in industries such as aerospace and biomedical, where strict regulations apply.

3.2.2. Polymers

Although AM can significantly reduce material usage and CO_2 emissions compared to traditional

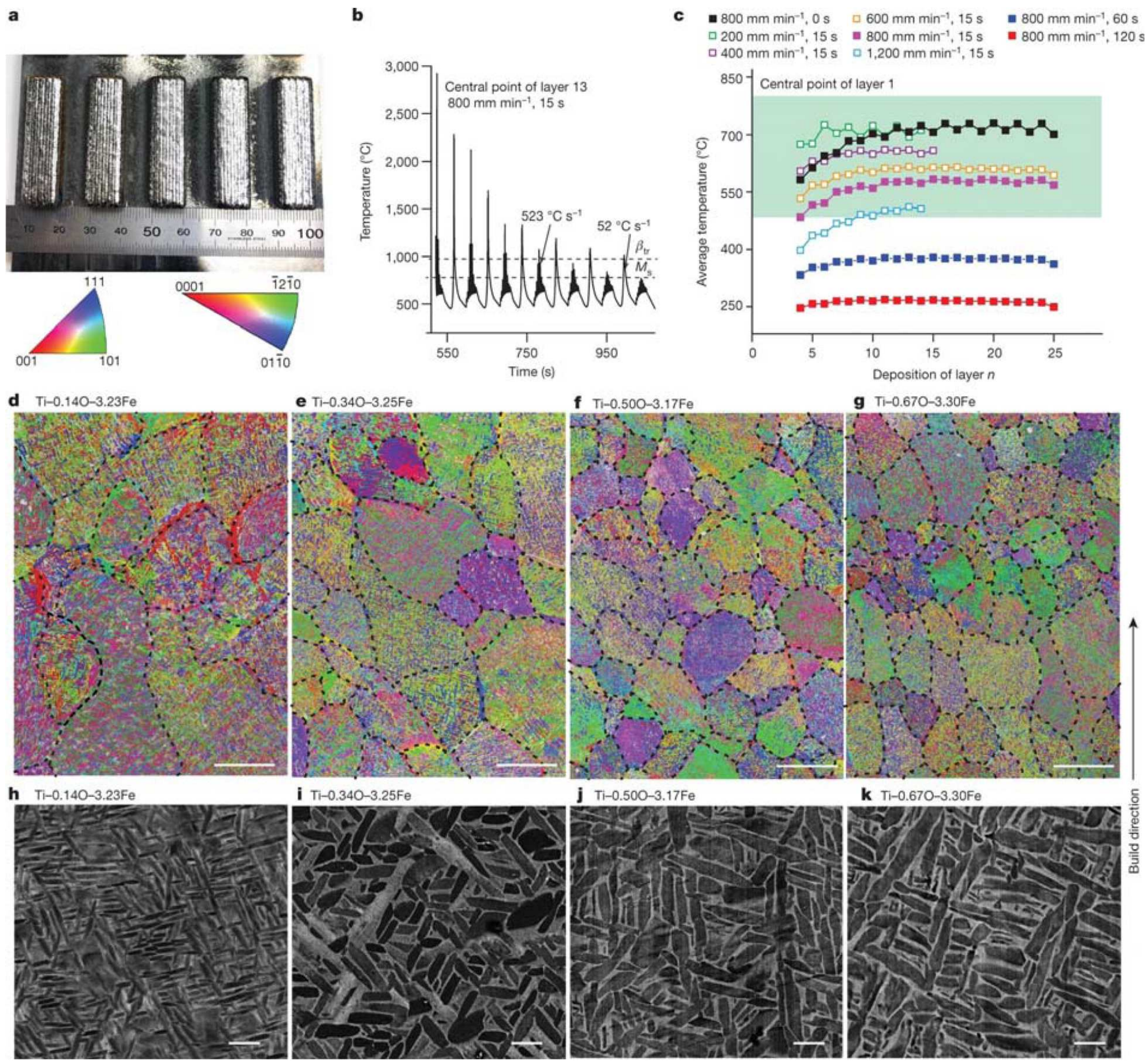

Figure 7. Microstructure of low-cost sustainable Ti-O-Fe alloys prepared by LDED: (a) sample images, (b) temperature profile during LDED, (c) process window (green area) determined by simulation, (d-g) Electron backscatter diffraction images of Ti-O-Fe alloys, (h-k) SEM images of Ti-O-Fe alloys. Reprinted from [80] under the Creative Commons CC BY 4.0 liscense.

manufacturing, it does not eliminate waste production. Developing sustainable polymers for AM is necessary to make polymer AM greener [101, 102]. Sustainable polymers are materials derived from renewable, recycled and waste carbon resources and their combinations, which at the end of life can be recycled, biodegraded or composted [103]. There are three questions to be addressed in sustainable AM polymers: (1) Is the source of AM polymer sustainable? (2) Is the processing of source materials for AM application sustainable? (3) Is the end of life of AM polymer product sustainable? As pointed out in [104], there may be trade-offs between sustainability indicators. For instance, bio-based material may be sourced sustainably, but its processing could require high energy consumption. Similarly, a fully degradable and recyclable thermoset polymer could be developed, yet it might depend on unsustainable synthetic materials. Nevertheless, as science continues to progress, novel solutions satisfying all the sustainability requirements should emerge. However, from the angle of AM, a fourth question must be addressed as well: (4) Is the performance of the AM polymer product satisfactory? There could also be trade-offs between sustainability and performance.

Sustainable AM polymers can be broadly classified into thermoplastic polymers and thermoset polymers. Some AM thermoplastics are already biodegradable (e.g. polylactic acid and polycaprolactone) or recyclable [105]. Even though, efforts are on-going to make them even 'greener' while preserving the desired

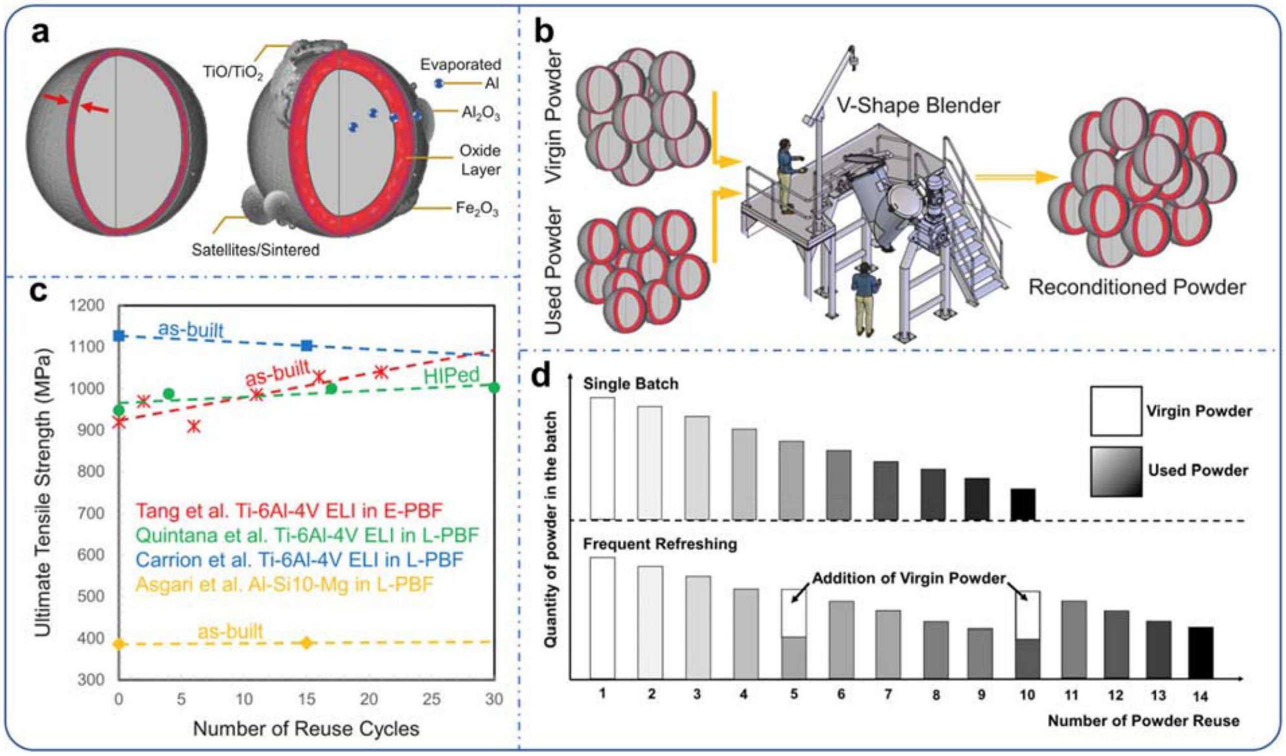

Figure 8. Powder reuse strategies for metal AM [94]: (a) schematic illustration of a virgin Ti64 powder particle and a reused Ti64 powder particle, (b) the reconditioning process of the used powder, (c) mechanical properties variation with increasing reuse cycles, (d) two typical powder refreshing strategies for increasing powder reusability. Reprinted with permission from Elsevier @ 2021.

performance, for example, blending wood with PLA [106], using upcycled plastics and biomass [107], using basalt fibers to replace carbon/glass fibres for reinforcement in polymer composites [108], and using bamboo fibres as reinforcement [109]. Reducing the ratio of synthetic part of AM polymer by natural materials is trending though, potential trade-offs among the four fundamentals should be minimised. Romani et al. [110] reported that PLA feedstock can undergo multiple recycling processes in large-format additive manufacturing systems with minimal thermomechanical degradation compared to traditional filament-based systems. By utilising granulated feedstock, they demonstrated improved sustainability and reduced processing steps while maintaining satisfactory material properties over several recycling cycles. This work highlights the potential of recycled thermoplastics in large-scale applications and emphasises the importance of integrating circular economy principles into AM processes. Similarly, Walker et al. [111] reported the successful recycling of carbon fibre-reinforced ABS machining waste for use in large-format AM. Their study revealed that the recycled material maintained competitive mechanical properties, including an improvement in Z-directional strength due to enhanced interlayer bonding. This work highlights the potential for integrating industrial waste streams into sustainable AM practices while addressing challenges in material consistency and performance. Additionally, the ability of AM to fabricate thermoplastic nanocomposites with enhanced thermal conductivity, as demonstrated by Yuan et al. [112], may provide opportunities to improve energy efficiency and sustainability in AM applications. Recently, there are some studies tapping on the concept of sustainable smart AM polymer, extending sustainable 3D printing to sustainable 4D printing [113–116]. As 4D printing is still in the infancy stage, these interesting developments are relatively less relevant to the industrial AM sustainably.

There are many reports on new sources for sustainable AM thermoset polymers [117–120]. However, chemical degradation of thermoset polymer with green solvent and reuse for AM presents a challenge. Recently, Machado et al. [121] reported a renewably sourced, circular photopolymer resin for AM (Figure 9). Unlike acrylates-based photopolymers that are primarily obtained from petroleum feedstocks, the reported photopolymer is derived entirely from lipoates, a renewable source. After stereolithography printing, the high-resolution parts can be efficiently deconstructed and subsequently reprinted in a circular manner. Like many commercial acrylic resins, the lipoate resins can be fine-tuned with fillers to adjust thermal and mechanical properties for different applications. For the first time, this sustainable AM thermoset polymer development demonstrates the feasibility of circular vat photopolymerization AM, which is traditionally believed to be impossible. Nevertheless, how to collect the 3D printed parts from various sources for effective and efficient recycling requires further exploration.

Besides the trade-offs issues, the role of machine learning and artificial intelligence in greener AM polymer development is worth discussing, especially in sustainable polymer design [122, 123]. As this topic has been covered in a recent excellent review [124], it will not be discussed here.

3.2.3. Concretes

Concrete AM is generally believed to be a green method compared to conventional casting of concrete parts owing to the advantages of AM such as formless process, material-on-demand and zero waste [125]. However, it is challenging to become greener because of the use of cement, which contributes the highest environmental impact [125–128]. Therefore, alternative approaches in concrete AM are needed to further minimise its environmental footprint. For example, the '3R' principle: reduce, replace and recycle, or a combination of them. Yoris-Nobile et al. compared low-clinker cement and geopolymer mortars, two cement replacements used in concrete AM, and concluded that low-clinker cement mortars are a favourable material due to a lower environmental impact and lower cost of materials, while the geopolymer mortars have a higher environmental impact due to the use of sodium hydroxide [129]. Jin et al. compared limestone calcined clay cement and ordinary Portland cement in AM for global warming potential and concluded that limestone calcined clay cement is effective in reducing environmental and allows a 36% to 46% reduction in global warming potential [130]. Skibicki et al. explored the potential of using fine recycled aggregates derived from waste of 3D printed concrete as a substitute for cement [131]. Replacement rates of was up to 20 vol% and the LCA analysis shows a significant reduction in mix cost (up to 24%) and a substantial decrease in equivalent CO_2 emissions (up to 48%). Many other studies on greener materials are interesting though, it is still challenging to achieve multiple objectives at the same time in terms of performance and multi-dimensional sustainability goals such as economy, environment and society. Nevertheless, new research angles other than materials may shed some light on future concrete AM, for examples, using renewable energy and locally sourced materials for AM [125].

3.2.4. Biomaterials

In recent years, there has been a notable push towards sustainable solutions across diverse industries, including the field of bio-ink development [132]. This momentum is driven by heightened environmental awareness of environmental issues and the urgent need to mitigate ecological footprints. As society becomes increasingly conscious of environmental issues, there is a growing recognition of the necessity for sustainable practices in bio-ink development. In response to this, the field of bio-ink development has witnessed a surge in interest towards creating environmentally friendly solutions. The concept of sustainable bio-inks revolves around using biomaterials and processes that are environmentally friendly and resource-efficient [133]. This holistic approach considers the entire lifecycle of bio-inks, from raw material sourcing to disposal. It emphasises the importance of adopting practices that minimise waste generation, energy consumption, and environmental pollution. By prioritising sustainability, researchers aim to create bio-inks that not only meet the technical requirements but also contribute positively to environmental preservation and resource conservation. Achieving sustainability in bio-ink formulation requires sourcing materials from sustainable sources, wastes, and their by-products, as well as utilising recombinant proteins. This multifaceted approach involves evaluating the environmental impact of each component and process involved in bio-ink production.

Recent research highlights microalgae as a promising source for sustainable bioink production. Microalgae, such as *Odontella aurita* and *Tetraselmis striata*, are known to accumulate high concentrations of triglycerides along with lipid-soluble, photoactive pigments like chlorophylls. These microalgae-derived triglycerides, with longer fatty acid chains and more double bonds than those in vegetable oils, offer a higher potential for post-functionalization. This makes them particularly suitable as precursors for light-based AM. In this study, microalgal extracts (mainly triglycerides with chlorophyll derivatives) were functionalised with photopolymerizable groups and used directly as bioinks, eliminating the need for additional photo-initiators (Figure 10). The successful fabrication of complex 3D microstructures, along with biocompatibility validated through cell viability assays, demonstrates the potential of these bioinks for sustainable AM [134].

An innovative approach used marine tunicates to develop a sustainable bioink for 3D bioprinting. The tunicate-derived extracellular matrix (dECM) bioink supports the growth and differentiation of neural stem cells (NSCs) into peripheral neurons, demonstrating excellent

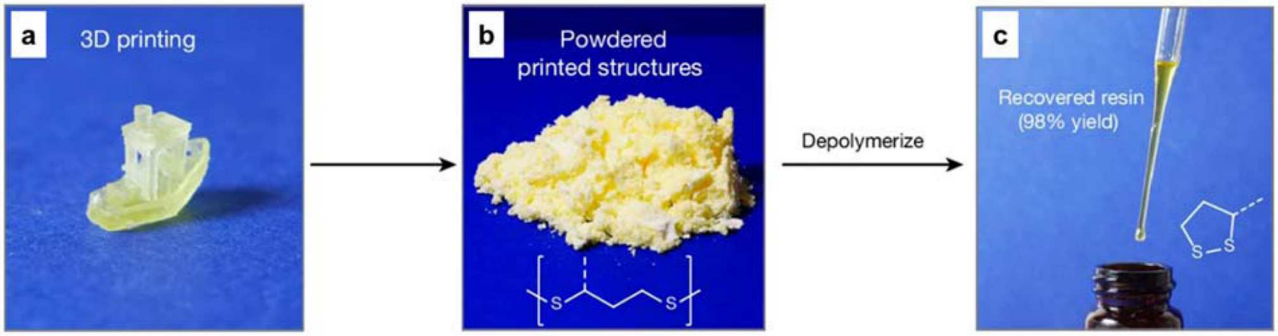

Figure 9. AM and depolymerization. Adapted from [121] under the Creative Commons CC BY liscense.

post-printing cell viability and preserving functionality after freeze–thaw cycles. This highlights its potential for long-term storage and clinical use. The study presents a robust, sustainable bioink for neural tissue bioprinting, with promising applications in translational medicine [135].

A promising strategy involves utilising plant-derived biomaterials as fundamental components of sustainable bio-inks. These biomaterials, such as alginate-based [136–138], agarose-based [139], and cellulose-based [140, 141] bio-inks, have attracted attention due to their abundance, biocompatibility, and tunable mechanical properties. Traditional production processes for these biomaterials typically involve pre-treatment, extraction, separation, and purification [142, 143]. However, with a growing emphasis on sustainable development, greener technologies have been employed to enhance extraction yield and product quality. Numerous studies have explored innovative methods like ultrasound-assisted [144], microwave-assisted [145, 146], extrusion-assisted [147], autoclaving [148], bio-ionic liquid [149, 150], and enzymatic [151, 152] approaches for more environmentally-friendly extraction methods. These advancements in extraction techniques improve the environmental sustainability of bio-ink production and reduce the environmental footprint of bioprinting processes.

Valorisation of wastes or by-products into useful bio-inks is essential for a more sustainable future. By repurposing materials that would otherwise be discarded, researchers can reduce waste generation and minimise environmental pollution. Collagen [153–156] chitosan [157] silk [158], and keratin [158–161] are examples of biomaterials that can be extracted from waste sources and used to create bio-inks with desirable properties. Collagen, a major structural protein in most animal tissues, can be sustainably extracted from various sources such as fish (scales and skin) and animal waste (skins, hides, bones, and connective tissues) [154–156]. Chitosan is primarily derived from marine-species such as shrimp shells, crab shells, and lobster/crayfish shells, providing a renewable source for chitosan extraction [157]. Emerging methods also enable the utilisation of silk waste or by-products (collecting discarded silk fibres from textile manufacturing processes or extracting silk proteins from waste sources) to produce silk-based bio-inks in a more sustainable manner [162, 163]. Keratins are commonly found in industrial wastes such as low-grade wool and trimmings, feathers that are often disposed through incineration or landfill. These unwanted waste products offer an abundant protein source that can be repurposed into printable bio-inks [164].

Additionally, recombinant protein-based bio-inks have been developed for various bioprinting applications [165–171]. These recombinant protein-based bio-inks include collagen [168–171], elastin [167], and spider silk [165, 166]. Recombinant proteins, produced through recombinant DNA technology, offer advantages such as large-scale production with high purity and consistency. They also allow for standardised manufacturing processes and quality control, as well as the production of proteins that are difficult to obtain from natural sources or modified for improved efficacy and safety. These recombinant proteins are typically produced using host organisms such as bacteria (*Escherichia coli*) [172], yeast (*Saccharomyces cerevisiae*) [173, 174], or mammalian cells [175]. When selecting the appropriate host organisms for recombinant protein production, critical factors to consider include protein quality, functionality, production speed and yield [176]. Through the thoughtful selection of sustainable and renewable biomaterials, adoption of eco-friendly manufacturing techniques, and innovative utilisation of wastes and its by-products, researchers strive to pave the way for a more sustainable future in bio-ink development.

3.2.5. Proteins & polysaccharides

The field of 3D food printing is advancing rapidly, driven by the need to integrate sustainable proteins and

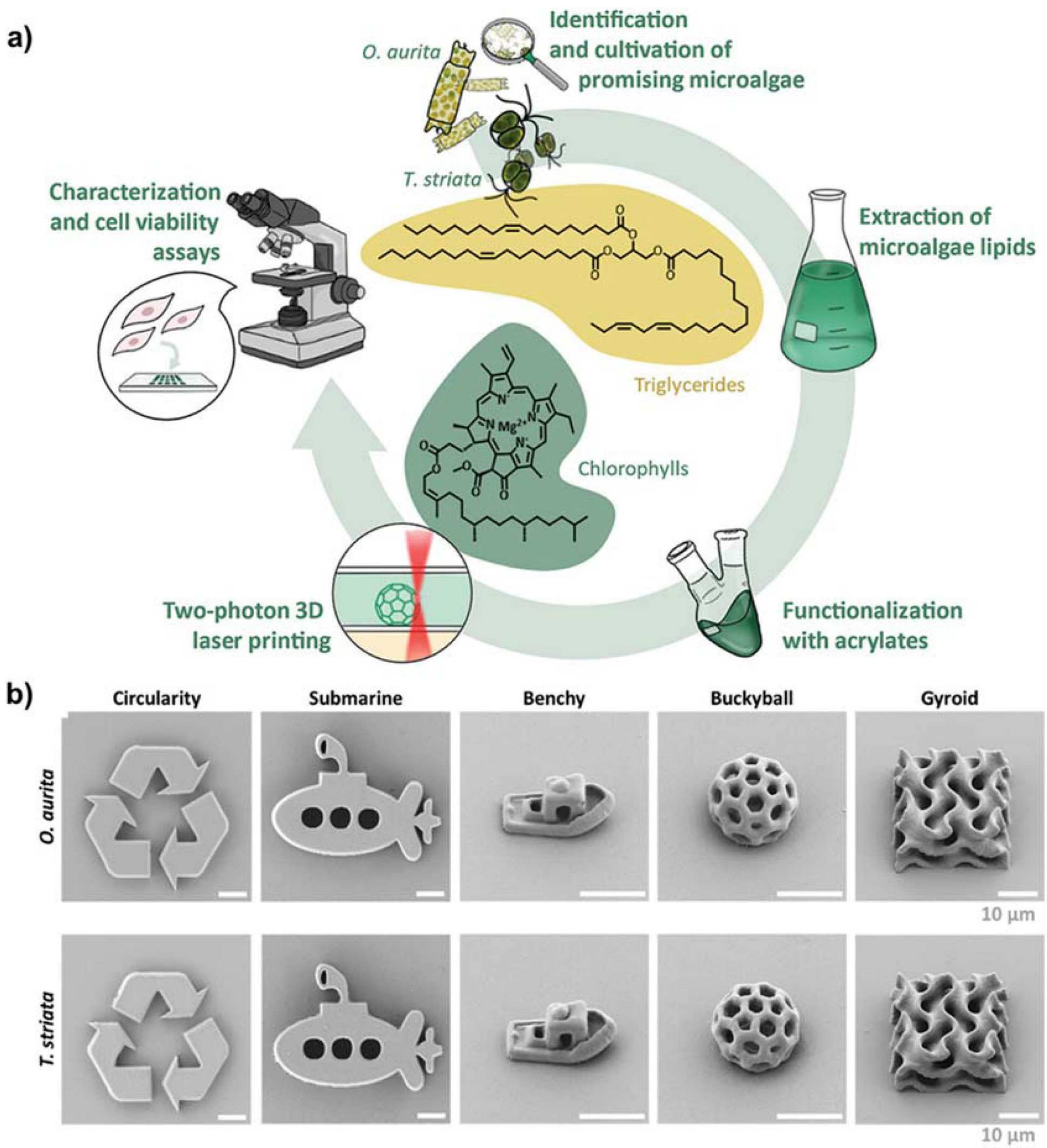

Figure 10. A schematic drawing demonstrating the use of sustainable microalgae-based material for AM. (a) Two microalgae strains, namely *Odontella aurita* and *Tetraselmis striata* were cultivated, and their extracts (mainly triglycerides with some chlorophylls) were functionalized for use as photopolymerizable materials in two-photon 3D laser printing. The printed structures were characterized, and their biocompatibility was assessed via cell viability assays. (b) Representative SEM images show different microstructures printed using the microalgae-based inks. Scale bar = 10 µm. Adapted from [134] under the Creative Commons CC BY liscense.

polysaccharides into eco-friendly food alternatives [177]. This technology responds to increasing consumer demand for plant-based diets while addressing environmental concerns associated with traditional food production methods [178]. By leveraging diverse sustainable ingredients, 3D food printing has the potential to revolutionise food manufacturing, offering solutions that cater to both nutritional needs and ecological goals.

Research has highlighted several plant-based proteins as promising candidates for 3D food printing. Soybeans, with their high protein content and fibrous texture, are widely used to create textured vegetable protein, effectively mimicking the mouthfeel of meat [179–181].

Similarly, pea protein provides essential amino acids like lysine and threonine, is easily digestible, and has shown health benefits such as lowering blood pressure [182–184]. Legumes like lentils can be processed into flour, creating customisable textures and flavours [185], while buckwheat, a gluten-free grain rich in protein, fibre, and antioxidants, offers excellent printability due to its favourable rheological properties [186, 187]. Buckwheat also has a quick growth cycle and requires minimal synthetic inputs, making it an environmentally friendly option. Although 3D food printing shows promise for plant-based alternatives, challenges remain in optimising print parameters to improve precision and expand the range of printable foods [188].

Polysaccharides also play a crucial role in enhancing the structural and functional properties of printed foods. These biodegradable polymers are ideal for both 3D and 4D printing due to their responsiveness to various stimuli [189]. Cellulose nanocrystals (CNCs), for instance, are used as rheological modifiers to improve the viscosity and thermal stability of protein-polysaccharide scaffolds, contributing to enhanced shape fidelity [190–193]. CNCs also add dietary fibre, thus enriching the nutritional profile of printed foods. Additionally, biodegradable hydrocolloids like alginate and agarose are popular in food printing for their biocompatibility and gelling capabilities, enabling the encapsulation of flavours and nutrients within printed structures [194, 195]. In addition to plant proteins and polysaccharides, 3D food printing research is exploring various sustainable ingredients that could transform the food printing landscape. Microalgae are rich in proteins, lipids, and antioxidants, making them excellent candidates for sustainable and nutrient-dense food inks [196–198]. Legumes and grains provide essential nutrients with a lower environmental impact compared to animal-based proteins [199]. Plant-derived starches also enhance printability by acting as natural binders, creating consistent textures in printed foods [200].

Alternative proteins from insect and fungi sources also contribute to the sustainability of 3D food printing. Insect proteins offer high-quality protein with minimal farming requirements and low greenhouse gas emissions, positioning them as a sustainable option for 3D food printing (Figure 11) [201]. Additionally, fungal proteins provide a meat-like texture and can be produced with a minimal environmental footprint [202, 203]. Food waste-derived ingredients are also being repurposed as 3D food printing materials, promoting a circular food economy by reducing waste [204–206]. In terms of structural stabilisers, hydrocolloids derived from seaweed, such as agar, carrageenan, and alginate, are biodegradable and renewable, providing essential support for printed foods while being environmentally friendly [207, 208]. Pectin, a natural gelling agent found in fruits, is also used in 3D food printing to create stable textures, supporting a sustainable approach to food production [209–211].

The integration of these sustainable proteins and polysaccharides into 3D food printing not only enhances the quality of printed foods but aligns with broader ecological sustainability goals. By sourcing these materials

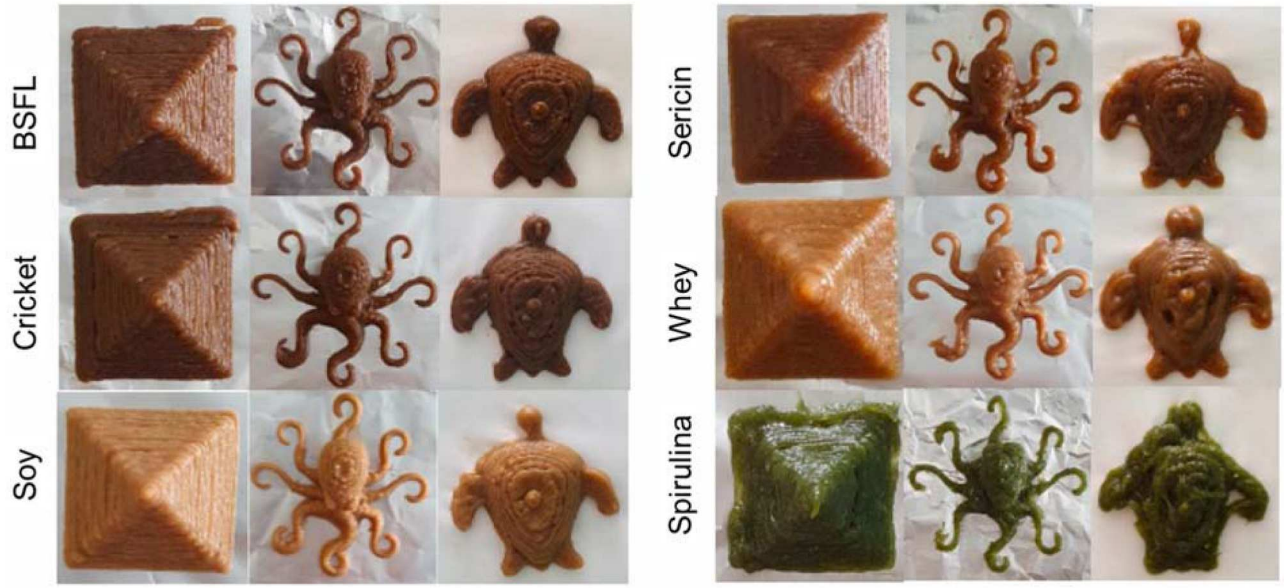

Figure 11. Representative images showcasing 3D-printed inks derived from diverse various food ingredients, including insect proteins from black soldier fly larva (BSFL), sericin, and cricket, as well as animal protein (whey), plant proteins (soy and spirulina) [201]. Adapted with permission from Elsevier @ 2022.

from renewable resources, researchers aim to reduce the environmental footprint of food production. With ongoing optimisation of printing techniques and the continuous exploration of new materials, 3D food printing is positioned to reshape food production, catering to consumer preferences for nutritious, eco-friendly alternatives while advancing ecological sustainability.

4. Sustainability after AM

4.1. Sustainable applications of metal AM

AM offers significant sustainability benefits across various applications. A notable example is General Electric LEAP engine, where the fuel nozzle was redesigned using AM [212]. This redesign not only reduced the number of parts from 20 to 1 but also cut the component's weight by 25%, leading to improved fuel efficiency. Such applications highlight the considerable potential of AM to achieve energy savings and waste reduction, offering a more sustainable approach for various industrial sectors [213]. Dr. Orme from Boeing reported that using AM to produce over 1,000 brackets in the galleys of the 787 Dreamliner reduced carbon emissions, waste sent to landfills, hazardous materials, water, and energy usage by 30%-39% compared to traditional manufacturing methods [31]. Instead of machining brackets from large metal blocks, AM used titanium wire melted and layered in a plasma field, significantly reducing material waste and associated energy consumption. Besides, in the Boeing EcoDemonstrator project, an optimised fire detector bracket produced via AM reduced its weight by 31% [31]. Although the carbon footprint of manufacturing the bracket with AM was slightly higher than traditional methods, the lighter part reduced the aircraft's fuel consumption and carbon emissions by 19% over its service life, far outweighing the initial carbon costs of production.

In addition to directly reducing emissions and energy consumption, metal AM plays a crucial role in advancing renewable energy technologies by enabling the design and fabrication of highly efficient, complex, and customisable components, thereby contributing indirectly to sustainability [214]. AM allow for precise control over material properties like porosity, conductivity, and surface area. These tailored structures have significantly enhanced the performance of energy conversion and storage devices such as fuel cells, solar cells, batteries, and supercapacitors. For instance, 3D-printed metal catalysts with hierarchical nanoporous structures provide superior surface area for catalytic reactions, improving efficiency in processes like CO_2 reduction and hydrogen generation [215–217]. Similarly, in batteries and supercapacitors, metal AM is used to create high surface-area electrodes, resulting in higher capacity and charge/discharge rates [218]. Additionally, 3D-printed metal-based heat exchangers and other thermal management devices are vital in optimising the thermal efficiency of energy systems [219, 220]. The versatility of metal AM thus presents a transformative solution for overcoming the efficiency and scalability challenges inherent in renewable energy technologies.

Additionally, metal AM techniques can also be used to repair damaged parts (not limited to AM-fabricated parts), which extends product life and reduces waste [221]. This is particularly favourable for industries like aerospace and automotive, where replacing entire components can be costly and resource-intensive. Compared to traditional welding techniques, such as tungsten inert gas welding and plasma transferred arc welding, the AM techniques (e.g. LDED) offers several benefits in parts repairing, including lower heat input, reduced warpage and distortion, and a lower dilution rate, while providing superior metallurgical bonding between the deposited layers [222]. As an application example, Keshavarz et al. [223] used LDED to successfully repair turbine blade tips, demonstrating the ability to produce crack-free deposits with excellent mechanical properties and oxidation resistance. Their study showed that LDED can restore structural integrity by improving tensile strength and creep resistance, even at high temperatures. Besides, Kim et al. et al. [224] used WAAM to repair nuclear pressurised water reactor (PWR) systems using a SA508 low alloy steel. They reported that WAAM could repair components without requiring post-weld heat treatment. This highlights WAAM's potential to extend the life of critical PWR components, reduce the need for full replacements, and improve sustainability by lowering material waste and energy consumption, as well as reducing radiation exposure during maintenance.

4.2. Sustainable applications of polymer AM

One study compared environment impact and cost of fused filament fabrication and injection moulding for mass-producing cosmetic plastic packaging [225]. It is concluded that fused filament fabrication is more expensive and environmentally impactful when compared to injection moulding, suggesting that AM may not be a sustainable solution for mass production of cosmetic plastic packaging. A similar conclusion is drawn when using AM to produce mobile covers [226]. However, these results are expected because AM is meant for small batch production and mass customisation rather than mass production. The sustainability benefits should be expected when producing small batches of customised cosmetic plastic packaging and mobile covers. Indeed, in another study comparing the sustainability of FDM and injection moulding, it is found that for a batch size lower than 14 parts FDM has a significantly lower environmental damage while for batch sizes above 50 parts, the injection moulding process generated less environmental impact [227].

Besides production volume, utilisation of waste materials also contributes to the sustainable application of polymer AM. In one study, unused polyamide from the selective laser sintering (SLS) process was collected for injection moulding of fuel-line clips [228]. Fuel-line clips are automotive components that are used to hold fuel lines in place for the lifetime of the vehicle. A life cycle assessment shows that recycling of polyamide powders from the SLS process brings overall energy and global warming potential benefits to the combined system of the SLS part and fuel-line clip. This study reveals an interesting pathway of polymer AM contributing to sustainability, i.e. AM waste becomes valuable materials for injection moulding. In another study, six supply chains of drinking water contains are compared, the one involving 3D extrusion printing with local waste feedstock shows a great potential for environmentally responsible production [229]. A special sustainable application of polymer AM is food waste valorisation such as vegetable waste [206], orange peels [230], jackfruit sees [231], for edible food, as well as banana peels for food packaging [232]. However, these studies lack life cycle assessment to confirm the positive sustainability benefits while moving towards the sustainable goal.

4.3. Sustainable applications of concrete AM

Wall construction is the most common application in concrete AM, especially for housing purposes (Figure 12). A recent study compared the sustainability performance of conventional method and AM method to build a 1 m^3 wall in the context of social housing in terms of four influencing factors: consumption of cement, transport distance, use of chemicals, and printing parameters [126]. It is found that the sustainability performance of both methods is similar, but increasing the use of supplementary cementitious materials in concrete AM can reduce the environmental impact caused by cement. It is also found that the width of the printing layer has the greatest contribution to the potential environmental impact because it strongly affects concrete consumption. Other studies drew similar conclusions on positive sustainability benefits of AM of a slab wall compared to conventional construction, because AM allows complex designs and the use of cement replacement materials [233–235]. Besides wall construction, a prefabricated bathroom unit constructed by concrete AM achieved an 85.9% decrease in CO_2 emissions and an 87.1% decrease in energy consumption as compared to the pre-cast method [236]. Nevertheless, there are still limited sustainability studies of large-scale concreate AM in the context of industrial construction. However, as a rule of thumb, when the complexity of building designs increases, conventional construction will take much longer time and cause more environmental impact compared to concrete AM.

5. Future perspectives

5.1. Artificial intelligence in AM

5.1.1. In-process control

Artificial intelligence (AI) has emerged as a transformative technology, offering significant opportunities to enhance sustainability in AM. Within AM in-process

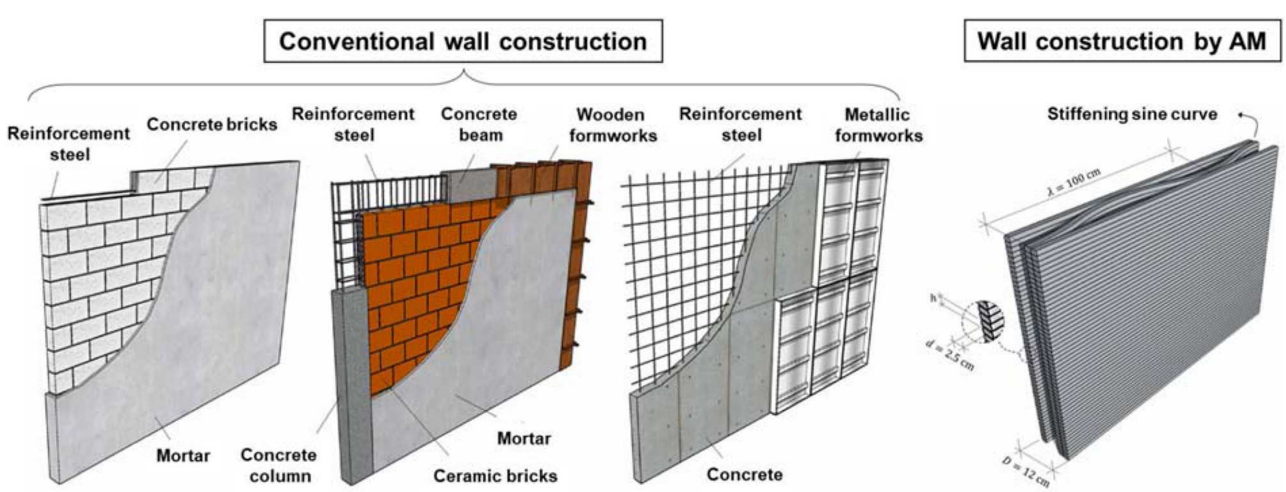

Figure 12. Wall construction by conventional methods and AM. Adapted from [126]. Reprinted with permission from Elsevier @ 2023.

control, AI is increasingly employed for real-time monitoring, defect detection, and quality assurance. Machine learning (ML), a core AI technique, enables predictive capabilities for defect formation and facilitates adaptive in-process control, enhancing both efficiency and product quality [46,237–240]. By optimising manufacturing in real time, ML techniques directly contribute to green manufacturing initiatives, reducing energy consumption, material waste, and CO_2 emissions [241].

In recent years, the integration of AI into AM processes has emerged as a powerful tool for enhancing defect detection and in-process control. Chen et al. [54] developed an acoustic-based ML-assisted in-situ defect detection framework for L-DED, showcasing the practical application of AI in defect monitoring. Their system employs deep learning, specifically convolutional neural networks (CNN), combined with a novel acoustic denoising technique to classify defects such as cracks and keyhole pores in real-time. This system achieved an overall accuracy of 89%, with 93% accuracy in keyhole pore detection. By integrating this AI-driven approach into LDED, the detection and classification of defects occur during the manufacturing process, allowing for immediate adjustments and reducing the occurrence of defective parts. The significance of this work for sustainability lies in its ability to detect defects early in the manufacturing process, minimising waste and energy consumption by reducing the need for post-production inspections and repairs. This real-time monitoring system aligns with the goals of green manufacturing by improving process efficiency, reducing material waste, and ensuring higher quality in AM.

The development of multisensor fusion techniques with AI has proven essential in advancing quality prediction and defect detection in additive manufacturing. A multisensor fusion-based digital twin framework is developed by Chen et al. [51] for localised quality prediction in LDED, achieving significantly higher accuracy compared to single-sensor approaches, as shown in Figure 13. Compared to single sensor, the integrated use of vision, acoustic, and thermal sensors enhances prediction accuracy by providing complementary data. Vision sensors capture geometric characteristics of the melt pool, revealing anomalies such as cracks or porosity, while thermal sensors monitor heat distribution, detecting potential defects caused by localised heat accumulation. Acoustic sensors add further sensitivity by capturing real-time sound emissions, which are particularly effective in detecting defects like cracks and keyhole pores. This fusion of data sources allows for a more comprehensive understanding of the process, resulting in a 96% prediction accuracy and a reduced false alarm rate of 4.4%, demonstrating the superior reliability of multisensor over single-sensor methods. These examples underscore potential of AI to enhance AM in-process control, improve sustainability, and reduce material waste through more accurate and efficient defect detection. However, AI-driven solutions also present potential risks, such as computational biases caused by skewed training datasets or overreliance on limited data sources, which can lead to inaccuracies in defect detection or quality prediction. To mitigate these risks, diverse and balanced datasets should be curated, and models should be regularly validated and updated with new manufacturing data. Additionally, incorporating explainable AI techniques can help build trust and ensure more transparent decision-making processes in practical applications.

5.1.2. Material design

For material design, AI also presents significant potential in accelerating sustainable material development for AM. On one hand, for material design, ML can significantly reduce the need for trial-and-error experiments, minimising resource waste [242]. On the other hand, with the assistance of ML, sustainable materials can be rapidly discovered and optimised for AM, thereby shortening the alloy design cycle and enhancing efficiency in material development.

For instance, the development of green steel has been reported with the assistance of ML. Tan et al. [243] developed a green cobalt-free Fe-Ni-Ti-Al maraging steel using ML and CALculation of PHAse Diagrams (CALPHAD) (Figure 14), focusing on leveraging the unique intrinsic heat treatment of LDED to achieve rapid precipitation hardening without the need for post-heat treatments. By tailoring the composition of this maraging steel, they optimised the precipitation kinetics of Ni_3Ti, enabling the formation of these hardening precipitates directly during the LDED process. This approach not only reduced energy consumption but also lowered CO_2 emissions associated with traditional post-heat treatments, aligning with sustainability goals. This work is significant for achieving sustainability because it eliminates the energy-intensive post-heat treatment commonly required for high-performance metallic materials, making the manufacturing process more energy-efficient. The in-situ formation of the strengthening phases during the AM process allows for the production of high-strength steel with minimised environmental impact, thus contributing to the advancement of green manufacturing technologies.

However, one of the main challenges in material development for AM is the high workload involved.

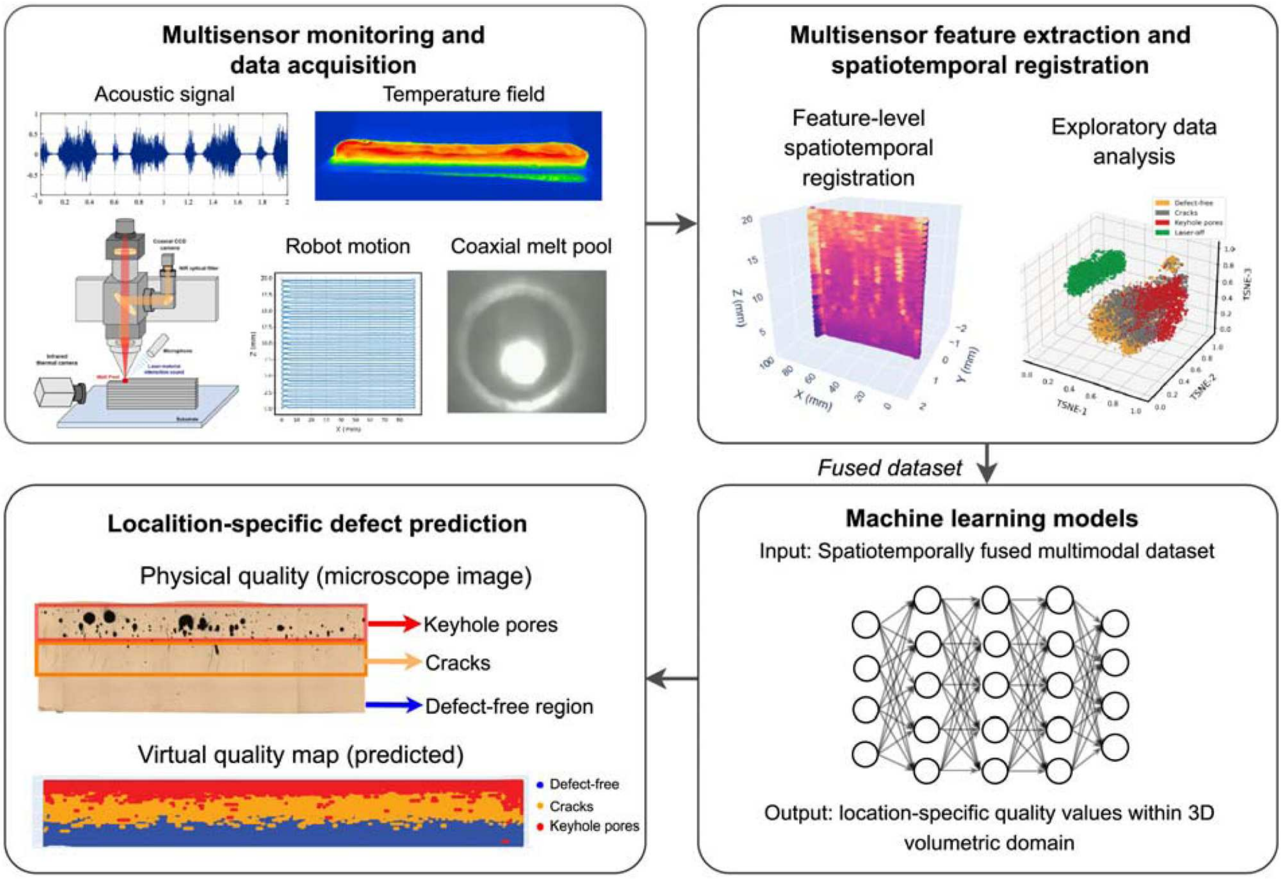

Figure 13. Multisensor fusion-based digital twin framework for defect prediction in L-DED [51]. Reprinted with permission from Elsevier @ 2023.

Taking the metal AM technique, LPBF, as an example, newly developed materials require optimisation of numerous process parameters, including but not limited to laser power, scan speed, hatch spacing, layer thickness, laser spot diameter, and scanning strategy [9]. This process optimisation for new materials is both time-consuming and energy-intensive. In this context, ML also offers new opportunities to accelerate material development for AM. For instance, ML has been applied to process optimisation [244], microstructure and property prediction [245], and the construction of process-structure–property linkages [78,246]. These applications can also significantly accelerate the material development process. This research direction deserves more attention in the near future.

5.2. Legalisation, regulatory frameworks and circular economy in AM

The expansion of AM in industry has introduced transformative potentials for sustainable production, but realising these benefits requires an integrated approach involving robust legalisation, regulatory frameworks and alignment with circular economy principles. These components are crucial to guiding AM toward environmentally responsible practices, minimising resource depletion, and promoting material recovery. With the advances in AM technologies, the regulatory environment must evolve accordingly to facilitate widespread adoption that aligns with sustainability goals. A comprehensive legal framework can support conscious AM practices by addressing material safety, lifecycle impacts and resource efficiency while encouraging circular economy principles.

5.2.1. Legalisation and regulatory frameworks

Regulatory frameworks governing AM need to address critical areas, including environmental standards, material safety, and intellectual property (IP) rights to support sustainable industry practices [14]. Currently, legal frameworks vary widely across regions, with some nations advancing specific regulations while others lack such measures. Harmonising these frameworks globally is essential to standardise sustainable practices and promote innovations without compromising environmental protection.

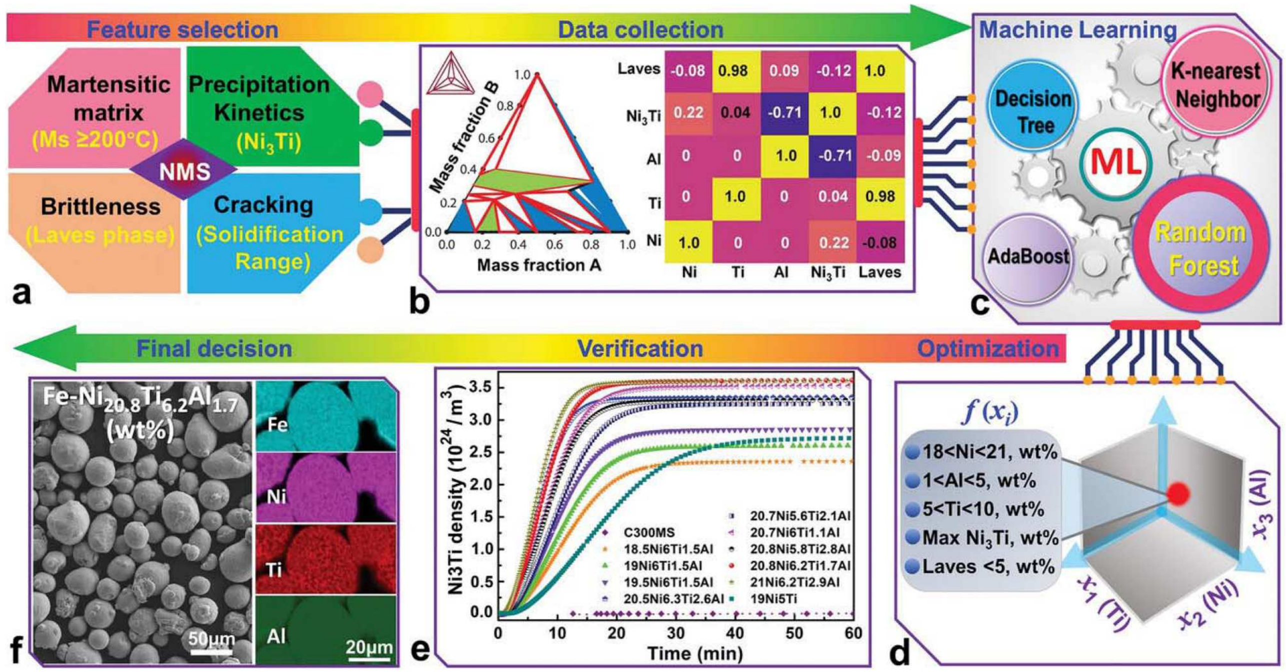

Figure 14. AI-driven design of green maraging steel for AM: (a) feature selections in the design of Fe–Ni–Ti–Al maraging steel, (b) dataset generated by Thermo-Calc software and the correlation matrix, (c) ML by various algorithms, (d) optimisation range of alloy composition, (e) precipitation behaviours of different compositions, (f) the morphology and composition of the designed Fe-20.8Ni-6.2Ti-1.7Al (wt%) maraging steel. Reprinted from [243] under the Creative Commons CC BY liscense.

A well-rounded regulatory approach should incorporate support for eco-friendly materials and processes [118, 247, 248]. This can be achieved through potential legal incentives such as tax rebates, grants, or subsidies tied to sustainable practices, motivating companies to invest in cleaner AM technologies. Standards based on ISO certifications, such as ISO 14001 for environmental management, can help companies implement sustainability from design through disposal by reducing waste, energy consumption, and emissions across production stages. In sustainable additive manufacturing, implementing a comprehensive set of standards helps organisations build robust environmental management practices. ISO 14001, a prominent standard within the ISO 14000 family, is fundamental for establishing effective 'Environmental Management Systems (EMS)'. However, other ISO standards complement ISO 14001 by addressing various dimensions of environmental management and sustainability, which together provide a well-rounded approach for AM sustainability.

Key ISO Standards Supporting ISO 14001

ISO 14004: This standard provides detailed guidelines for establishing, maintaining, and improving an EMS, complementing ISO 14001 by offering further insights into environmental management principles. It assists organisations in refining their EMS to better address sustainability goals.

ISO 14006: Focusing on eco-design integration, ISO 14006 offers guidance on incorporating environmental considerations directly into product design and development. This standard promotes sustainability from the initial design phase, aligning well with AM's potential for material and energy efficiency.

ISO 14015: This standard provides a framework for the environmental assessment of sites and organisations. It allows AM companies to evaluate the environmental impact of production facilities, enabling informed decisions to mitigate site-specific impacts and improve overall sustainability.

ISO 14031: With a focus on environmental performance evaluation, ISO 14031 guides organisations in assessing and reporting their environmental impact, aiding them in tracking their progress toward sustainability goals. This standard is particularly useful for AM businesses seeking to monitor improvements and demonstrate commitment to environmental performance.

ISO 45001: Although focused on occupational health and safety, ISO 45001 follows the same High-Level Structure (HLS) as ISO 14001, facilitating integration with EMS. For AM companies, adopting ISO 45001 can enhance worker safety while maintaining environmental goals within an integrated management system.

ISO 50001: Centred on energy management systems, ISO 50001 shares the structured approach of ISO 14001 but focuses specifically on efficient energy management. Its application helps AM organisations reduce energy-related environmental impacts, which is crucial given AM's energy-intensive processes.

In addition to environmental standards, regulatory guidelines on material sourcing, production processes, and end-of-life management can reinforce sustainable practices in AM [249]. For example, mandates for using recyclable materials or requiring lifecycle assessments could help companies evaluate and mitigate their environmental impact. A balanced IP framework is also essential, especially given the ease of replication inherent to AM. Adapting IP laws to protect digital AM design files while encouraging sustainable innovation can help protect creators' rights and encourage a sustainable design culture. Finally, targeted incentives can further foster a culture of sustainability in the AM industry. By offering tax benefits for eco-friendly materials use or funding for research into sustainable AM, governments can drive investment into cleaner production methods and reinforce a commitment to sustainable practices.

5.2.2. Circular economy in AM

The principles of a circular economy (CE) promote continuous material reuse, positioning AM as a sustainable production approach [250, 251]. AM technologies naturally align with CE principles due to their ability to minimise material waste and enable on-demand production, reducing excess inventory needs. Additionally, the flexibility of AM supports remanufacturing and recycling, lessening the demand for raw materials and diminishing environmental strain. For instance, metal AM waste can be reprocessed into powder for reuse [250, 252], while innovations in biodegradable polymers help reduce plastic waste within AM processes [253]. Furthermore, AM has been shown to upcycle food waste, such as orange peel, into edible products, contributing to a more sustainable and circular food manufacturing system [230].

Adopting circularity in AM requires a closed-loop ecosystem where material flows are carefully managed to encourage reuse and recycling throughout the product lifecycle [254, 255]. This includes incorporating material tracking, reverse logistics, and modular, repairable designs that extend product longevity. With these frameworks, AM can significantly contribute to a circular economy by promoting resource efficiency, minimising waste, and enhancing lifecycle management. Integrating legal, regulatory, and CE principles in AM presents a significant opportunity to advance sustainability goals. Collaboration among policymakers, industries, and research institutions will be essential to create adaptive, comprehensive frameworks that enable AM to fulfil its potential as a catalyst for sustainable industrial transformation. As the AM industry evolves, strengthening these components will be critical for fostering a resilient, resource-efficient, and environmentally responsible manufacturing landscape.

The key components of a circular economy framework in AM include: (1) Material Recovery and Recycling: A circular economy framework in AM should emphasise material recovery and recycling systems. Policies can encourage partnerships between manufacturers and recycling facilities to repurpose AM waste effectively, ensuring that unused or discarded materials are collected and recycled. (2) Design for Sustainability: Frameworks should support sustainable design practices such as design for disassembly and modular design. These approaches make products easier to repair, upgrade, or recycle, reducing waste and extending product lifespan. Education and Training: To support circularity in AM, educational programmes focusing on sustainable design principles, material selection, and lifecycle thinking are essential. Training designers and engineers in these principles fosters a culture of sustainability across all production levels. (3) Cross-Sector Collaboration: Implementing a circular economy requires collaboration among manufacturers, policymakers, researchers, and consumers. Establishing platforms for dialogue can facilitate knowledge sharing and innovation in sustainable practices within the AM sector.

As the legal and regulatory frameworks around AM evolve, they must prioritise environmental considerations and promote circular economy initiatives through innovative design practices and cross-sector collaboration. By doing so, AM can significantly advance sustainability goals within the broader manufacturing industry.

6. Summary and research trends

6.1. Summary

In summary, AM presents new opportunities for achieving sustainability. The inherent benefits of AM—such as greater flexibility, high design freedom, and near-net-shape forming capability—can offset its high costs, particularly in small-batch and/or functional parts production [256]. Additionally, AM enables the rapid fabrication of customised parts, reducing the need for extensive storage. However, critical challenges such as energy-intensive processes, material inefficiencies in certain applications, and scalability issues must also be acknowledged to provide a balanced perspective. Overall, sustainability is expected to be achieved by AM from the following key aspects (Figure 15):

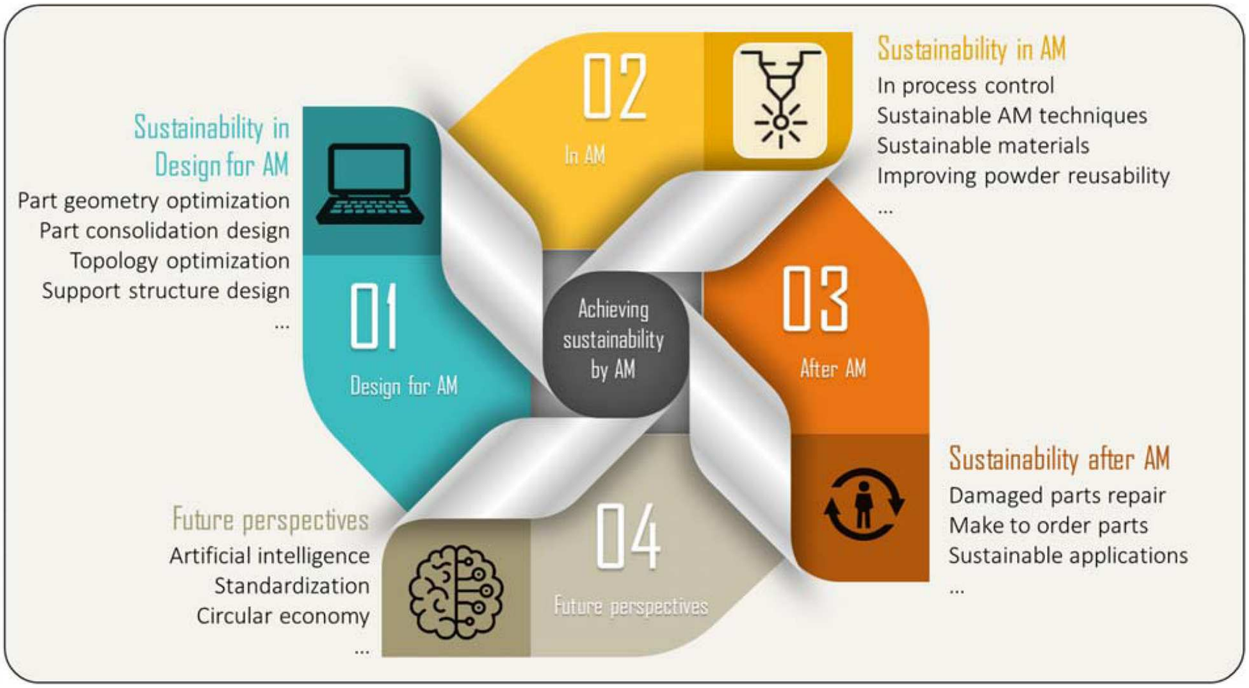

Figure 15. A summary on achieving sustainability by AM: design for AM, in AM, after AM and future perspectives.

(1) *Achieving sustainability in design for AM*: Achieving sustainability in DfAM involves both environmental and economic evaluations, though studies explicitly focused on sustainability remain limited. Typically, DfAM sustainability assessments compare AM to conventional manufacturing, offering case-based evidence of AM's advantages in reducing environmental impact. Recent research highlights the importance of understanding and optimising DfAM's sustainability potential, specifically through lifecycle analyses and implementing sustainable design practices. DfAM strategies, such as cellular structures, part consolidation, and topology optimisation, have demonstrated positive impacts by reducing material use and improving component efficiency. However, some complex designs may increase energy consumption and CO_2 emissions due to longer manufacturing times, suggesting a trade-off between mass reduction and production efficiency. Part consolidation minimises assembly needs and enhances part longevity, though it may also elevate toxicity risks in certain AM methods like binder jetting. The use of tools like Eco-Design for AM (EcoDfAM), machine learning, and sustainability-focused topology optimisation can help streamline sustainable design in DfAM. Despite these advancements, more systematic exploration of DfAM tools, including artificial intelligence and advanced simulation frameworks, is required to effectively address the trade-offs between sustainability and manufacturing complexity. Further exploration of AI-driven DfAM tools and advanced simulation frameworks is recommended to achieve a balance between manufacturing complexity and sustainability goals.

(2) *Achieving sustainability in AM*: Achieving sustainability in AM involves optimising in-process control and material utilisation. Advanced in-process control techniques, such as optical and acoustic sensors, enable real-time defect detection and adaptive in-process control, significantly reducing material waste, energy consumption, and printing failures [46]. These technologies enhance the efficiency of AM by minimising rework and reducing the need for energy-intensive post-processing treatments. Furthermore, the use of recycled materials, such as machining chips and swarf, as AM feedstock presents a promising route for reducing material waste. The development of sustainable alloys—those with increased oxygen tolerance or that require no post-heat treatment—also contributes to sustainability by eliminating costly and energy-intensive processing steps [91]. Additionally, improving powder reusability in powder-based AM methods (e.g. LPBF) lowers raw material costs and minimises waste, particularly when effective powder refreshing strategies are implemented [94]. Nevertheless, the study identifies challenges such as the energy-intensive nature of laser-based techniques and the limited availability of fully recyclable

AM feedstocks. Tackling these challenges requires prioritising energy-efficient AM processes and scalable recycling systems. Overall, the in-process control and the use of sustainable materials reduce the environmental impact of AM while promoting a more efficient and cost-effective manufacturing cycle, contributing to broader sustainability goals in the manufacturing sector.

(3) *Achieving sustainability after AM*: Metal, polymer, and concrete AM techniques contribute to sustainability through diverse applications. Metal AM can extend product life by repairing damaged parts, as demonstrated in the aerospace and nuclear industries, where LDED and WAAM improve repair efficiency, reduce waste, and lower environmental impact [221]. Metal AM also advances renewable energy technologies by creating high-efficiency components for fuel cells, batteries, and heat exchangers [214]. For polymer AM, while not suitable for high-volume production due to environmental costs, it shows sustainability potential in small batch customisation, using recycled and waste materials. Studies indicate that reusing polyamide waste from AM for injection moulding reduces overall environmental impact. Furthermore, polymer AM enables innovative uses of food waste for sustainable packaging and even edible applications. Concrete AM, widely used in wall construction, demonstrates potential sustainability benefits by allowing for complex designs with reduced cement consumption, especially when using supplementary materials. In comparison with traditional construction, concrete AM also shows a significant reduction in CO_2 emissions and energy consumption, as seen in prefabricated bathroom units. Nevertheless, these sustainability benefits are not universal. For instance, polymer AM processes may still pose challenges due to limited recyclability, and concrete AM methods often require extensive validation for long-term durability. Expanding research on these limitations is critical to fully realise the post-AM sustainability potential. Although more research is needed, AM's adaptability to sustainable practices positions it as a valuable approach in promoting sustainability across various industries.

(4) *Future perspectives in achieving sustainability by AM*: AI is poised to transform AM, especially in-process control and material design. AI enables real-time defect monitoring and adaptive in-process control, reducing waste, energy consumption, and enhancing quality through ML-based predictive models [51]. In material design, AI accelerates sustainable alloy development by optimising compositions and reducing energy-intensive steps, as illustrated by recent advancements in green steel design without post-heat treatment requirements [243]. Despite its potential, integrating AI into AM requires addressing significant challenges, such as the demand for large, high-quality datasets and the computational cost of real-time decision-making systems. Legal frameworks, regulatory standards, and circular economy principles are equally crucial to drive AM's sustainable growth. Establishing comprehensive regulatory guidelines and integrating circular economy strategies, such as material recovery and recycling, can further reduce resource depletion and environmental impact. Key standards like ISO 14001 for environmental management are essential, while targeted incentives, eco-friendly material mandates, and IP protections will support sustainable innovation in AM. The study concludes that interdisciplinary collaboration among industries, policymakers, and research institutions is vital to achieve a resource-efficient manufacturing ecosystem, positioning AM as a key contributor to sustainable industrial transformation.

6.2. Research trends

Trend 1: Integration of sustainability metrics in DfAM from early design stages

There is a growing need to incorporate sustainability metrics directly into the DfAM, rather than post-manufacturing evaluation. Future research could focus on developing tools and algorithms that allow designers to embed sustainability metrics, such as CO_2 emissions, material efficiency, and energy use, directly into CAD software during the early design stages. Additionally, research should address how to standardise sustainability criteria for cross-industry applications and ensure compatibility with various AM technologies. Establishing methodologies like LCA and carbon footprint analysis as routine components in DfAM, allowing designers to visualise and evaluate sustainability impact early on.

Trend 2: Developing sustainable feedstock material for AM

A key trend in advancing sustainability in AM is the development of sustainable feedstock materials through: designing low-cost raw materials and/or recycling waste materials as AM feedstock. Research avenues could include improving the mechanical performance of recycled feedstocks and investigating alternative chemistries for low-cost alloys tailored to specific AM processes. Additionally, studies should explore the environmental lifecycle impacts of these feedstocks compared to virgin materials. Techniques such as friction-stir AM and continuous extrusion processes enable the transformation of waste material into valuable feedstock for AM methods like LDED and WAAM [74]. Together, these approaches not only reduce reliance on virgin materials but also support circular economy principles by maximising resource efficiency and minimising environmental impact in AM production.

Trend 3: Developing sustainable AM processes with enhanced cost efficiency, high build rates, and reliability

A prominent research trend in AM is the pursuit of innovative, sustainable methods that emphasise cost efficiency, high build rates, and process reliability. Specific research questions could include: What design modifications or materials are required for scalability in AM methods? How can process monitoring and control systems be improved to enhance both deposition rate and precision? Furthermore, how can emerging technologies like multi-laser systems or hybrid AM methods be optimised to align with sustainability goals? This involves the exploration of AM techniques that optimise material use, reduce energy consumption, and increase production speed, making AM more viable for large-scale and cost-sensitive applications. The overarching goal is to develop AM methods that are adaptable, resource-efficient, and capable of supporting high-volume manufacturing sustainably across diverse industries. Looking ahead, the integration of diverse materials such as metals and polymers in AM opens up possibilities for multi-functional devices, combining strength, flexibility, and conductivity for advanced applications [257]. Moreover, AM's potential for in-situ manufacturing in extraterrestrial environments, such as on the moon, offers groundbreaking solutions for sustainable construction and energy generation in space exploration [258].

Trend 4: Applications of ML in accelerating material development and process parameters optimisation for AM

ML is transforming materials development and process parameters optimisation in AM, driving more sustainable and efficient advancements [17]. In materials development, ML reduces the need for extensive trial-and-error experimentation by enabling data-driven predictions of microstructure, properties and performance, thus accelerating alloy design cycles. Additionally, ML aids in optimising AM process parameters by constructing process-structure–property linkages. These predictive capabilities enhance material performance while minimising energy consumption and waste, aligning with green manufacturing goals. Future work could focus on integrating ML models with physical simulations for enhanced accuracy in predicting AM outcomes. Another research question could investigate how to create explainable ML models for AM, which would help build trust and enable wider adoption across industries.

Trend 5: Creating digital twin in AM for achieving sustainability

By creating a real-time, virtual representation of the AM process, digital twin allows for precise monitoring, simulation, and control of the entire production workflow [51]. This approach not only enables faster iteration and testing in material development but also enhances process optimisation by predicting defects, improving quality, and reducing waste. Additionally, digital twin contribute to sustainability by minimising the need for physical prototypes, cutting down energy consumption, and optimising resource utilisation. Through continuous feedback and adaptation, digital twin empower manufacturers to achieve higher efficiency and sustainability in AM, promoting greener and more cost-effective production methods. Future research could focus on enhancing the fidelity of digital twins by incorporating real-time machine learning models and advanced sensing technologies. Potential questions include: How can digital twins be standardised across different AM technologies? How can interoperability be improved for seamless integration with existing manufacturing systems?

Trend 6: Reduce post-processing treatment after AM

A significant research trend in AM is the reduction of post-processing treatments, which can be time-consuming, energy-intensive, and costly. For metal AM, one area of focus is the development of heat treatment-free alloys that harness the intrinsic thermal cycling of AM processes to achieve the desired microstructure and properties during printing, eliminating the need for conventional heat treatments like high-temperature annealing [91,243]. This innovation improves energy efficiency, reduces production time, and lowers costs. Additionally, advancements in AM surface quality aim to reduce the need for post-processing steps such as edge cutting, surface trimming, and machining. There is also increasing interest in replacing traditional hot isostatic pressing (HIP) and high-temperature heat treatments with low-temperature heat treatments, further lowering energy consumption and minimising the environmental impact of AM. These efforts collectively contribute to making AM more sustainable and cost-effective by streamlining the manufacturing process and reducing reliance on resource-intensive post-processing techniques.

Trend 7: Achieving automated zero-defect AM through in-situ process monitoring and closed-loop control

A key trend in AM is the use of in-situ process monitoring and closed-loop control systems to achieve zero-defect parts, especially those with complex geometries. Optimised process parameters often suffice for simpler shapes (e.g. cubes), yet when manufacturing more intricate parts, defects can emerge due to varying thermal histories across different regions [54]. These localised defects can significantly affect the structural integrity of the component. In-situ monitoring systems enable real-time defect detection and correction within the AM process, effectively reducing failure rates and enhancing overall part quality. For instance, upon detecting defects, corrective measures—such as dynamically adjusting process parameters or removing defective layers via machining—can be implemented to maintain a zero-defect standard [46]. This approach proves particularly valuable in the production of large or highly complex components, where conventional manufacturing methods may fall short in achieving the same level of microstructural precision and defect control. Future work could address how AI-enhanced monitoring systems can provide early-stage defect prediction and prevention, and how closed-loop controls can be made adaptable to a wider range of AM technologies.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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