

## Exploring Additive Manufacturing of Sustainable Bio-Based Polylactic Acid Products for Local Handicraft Development

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### Abstract

The advancement of bio-based materials combined with additive manufacturing (AM) technology has created new opportunities for sustainable innovation and local economic empowerment. This study investigates the potential of polylactic acid (PLA) as a biodegradable and sustainable polymer derived from natural resources such as corn starch and sugarcane. Although PLA offers promising alternatives to petroleum-based plastics, their integration into community-based production through additive manufacturing remains underutilized. Local handicraft in micro, small, and medium enterprise (MSME) often lack the knowledge, tools, and technical capacity to transition from traditional manufacturing to digital fabrication methods. Consequently, opportunities to improve product quality, environmental sustainability, and market competitiveness remain untapped. In this study, PLA was applied for handicraft-based product development using 3D printing. The study was conducted as part of a community development aimed at strengthening MSME operating in the creative and handicraft sector of Padang City, Indonesia. The program introduced participants to the principles of sustainable design and digital fabrication, through a structured approach. This involved capacity building workshop, design mentoring, and hands-on prototyping. Local craftsmen were guided in adapting crafting techniques to incorporate 3D printing using PLA filaments, enabling the creation of eco-friendly and customizable products. This study showcases how merging craftsmanship with modern digital technology can empower local community. The study shows that integrating additive manufacturing (AM) into local handicraft production improves design flexibility (14%), reduces material waste (7%), enhances customization (12%), and strengthens technical skills (7%). These outcomes demonstrate increased efficiency, sustainability, and competitiveness, supporting innovation and resilience in localized handicraft enterprises.

### Keywords

Additive Manufacturing, 3D Printing, Bio-based PLA, Local Handicraft, MSME

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## Introduction

The development of bio-based materials in combination with additive manufacturing (AM) technologies has opened significant avenues for sustainable innovation and local economic development. By enabling the use of renewable and biodegradable materials, AM supports circular economy strategies and reduces material waste through precise layer-by-layer deposition rather than subtractive removal (Kumar et al., 2022; Peng et al., 2023; Singh et al., 2022). Compared to conventional manufacturing, AM enhances resource efficiency and lowers emissions when integrated with sustainable material strategies (Peng et al., 2023). The integration of bio-based materials with AM further supports decentralized and distributed production models (Singh et al., 2022). These approaches enable communities to utilize locally available biomass, agricultural by-products, or recycled bio-waste to manufacture functional components, construction elements, and consumer goods. As a result, supply chains are shortened and transportation-related emissions are reduced (Kumar et al., 2022). Localized production can also strengthen regional economies by encouraging small-scale manufacturing initiatives, supporting local expertise, and creating skilled employment opportunities in digital fabrication and material processing (Peng et al., 2023). This localized and digitally enabled production model aligns with broader discussions on sustainable localized production systems and collaborative innovation frameworks (Singh et al., 2022).

From a design and performance standpoint, AM enables precise control over geometry and internal architecture, allowing material-efficient structures that meet specific mechanical and functional requirements (Zhang et al., 2022; Torres-Carrasco & Puertas, 2023; Wang et al., 2022). The use of biodegradable polymers such as polylactic acid (PLA) and bio-based composites further expands application possibilities across industries while strengthening circular design strategies (Wang et al., 2022). Additive manufacturing enables on-demand, small-scale production embedded within regional settings, allowing communities to capitalize on locally available bio-based resources while reducing dependence on globalized supply chains (Torres-Carrasco & Puertas, 2023). These decentralized systems lower the carbon footprint associated with long-distance logistics and strengthen supply chain resilience, particularly in regions with limited industrial infrastructure (Zhang et al., 2022). The inherently digital nature of AM enables modular and flexible production networks in which design data can be transmitted electronically and manufactured locally, supporting distributed and resilient systems (Wang et al., 2022).

Bio-based AM materials can be engineered to meet specific mechanical and environmental performance requirements, thereby improving resource efficiency and lifecycle performance (Li et al., 2022; Farah et al., 2023; Ghaffar et al., 2022). Advances in material formulation and process control allow designers to fine-tune properties such as stiffness, strength, thermal behavior, and biodegradability through geometry and composition rather than increased material use (Farah et al., 2023). Circular economy frameworks integrated with AM further enhance collaborative innovation and lifecycle-based product development (Ghaffar et al., 2022). Digitally enabled networks enhance system resilience by allowing production to be reconfigured or relocated in response to supply disruptions, resource constraints, or shifting demand (Li et al., 2022). In the context of bio-based materials, this flexibility supports the integration of locally sourced and recycled feedstocks into distributed production models while advancing circular economy goals (Ghaffar et al., 2022). Modular and digitally connected production structures also lower barriers

to entry for small and medium-sized enterprises (SMEs), fostering innovation and broader participation in industrial value chains (Farah et al., 2023).

Together, these developments position bio-based AM as a central driver of sustainable industrial transformation by advancing circular production models, improving material efficiency, and enabling decentralized fabrication systems (Bai et al., 2022; Del Giudice et al., 2023; Nascimento et al., 2022). By integrating environmental responsibility with economic inclusivity and technological adaptability, bio-based AM supports resilient and distributed manufacturing structures capable of responding to sustainability imperatives across sectors (Nascimento et al., 2022). Its capacity to align digital innovation with localized material sourcing reinforces its contribution to sustainability transitions in both developed and emerging economies (Del Giudice et al., 2023). Although PLA offers a promising alternative to petroleum-based plastics due to its renewable origins and biodegradability, scaling its use in additive manufacturing requires supportive ecosystems, technical expertise, and coordinated policy frameworks (Bai et al., 2022). While PLA is widely compatible with technologies such as fused filament fabrication, its integration into community-based and small-scale production contexts remains uneven, particularly where access to training, infrastructure, and innovation networks is limited (Nascimento et al., 2022).

These enterprises typically rely on traditional, craft-based production methods embedded in local culture and skill sets. Shifting toward digital fabrication requires access to appropriate equipment and competencies in digital design, material optimization, and machine maintenance (Müller et al., 2022; Sassanelli et al., 2023; Troise et al., 2022). Without adequate technical capacity and institutional support, MSMEs may struggle to adopt additive manufacturing effectively (Troise et al., 2022). Beyond technical constraints, economic and institutional factors further restrict uptake. Initial investment costs, limited training opportunities, and insufficient innovation support can deter small-scale producers from exploring PLA-based AM (Sassanelli et al., 2023). Consequently, opportunities to combine sustainable materials with localized, flexible production remain underexploited (Müller et al., 2022). Addressing these gaps through targeted capacity-building initiatives and supportive innovation ecosystems is essential for enabling community-based enterprises to harness the environmental benefits of PLA while strengthening local economic resilience (Troise et al., 2022; Boffa et al., 2022).

In this study, PLA was applied for handicraft-based product development using 3D printing through workshops aimed at strengthening MSMEs in the creative sector of Padang City, Indonesia. Such community-oriented AM initiatives align with evidence that decentralized manufacturing can stimulate local innovation ecosystems and employment while promoting sustainable industrialization (Klerkx & Begemann, 2023). Integrating sustainable materials with digital fabrication training further supports lifecycle performance optimization and circular production strategies. These initiatives demonstrate how distributed additive manufacturing combined with bio-based materials can contribute to inclusive and sustainable local economic development (Rejeb et al., 2022).

## Methodology

The workshop series introduced participants to the principles of sustainable design and digital fabrication through a structured and progressive approach. It combined foundational theoretical concepts with hands-on activities to build an understanding of material sustainability, design thinking, and additive manufacturing processes using Fused Deposition Modelling (Figure 1). Participants were guided through key stages, including ideation, digital modeling, and basic fabrication workflows, enabling them to connect environmental considerations with practical design decisions. By integrating sustainability concepts with applied digital skills, the program aimed to foster awareness of responsible production practices while equipping participants with the competencies needed to explore innovative, resource-efficient design solutions in a real-world context.

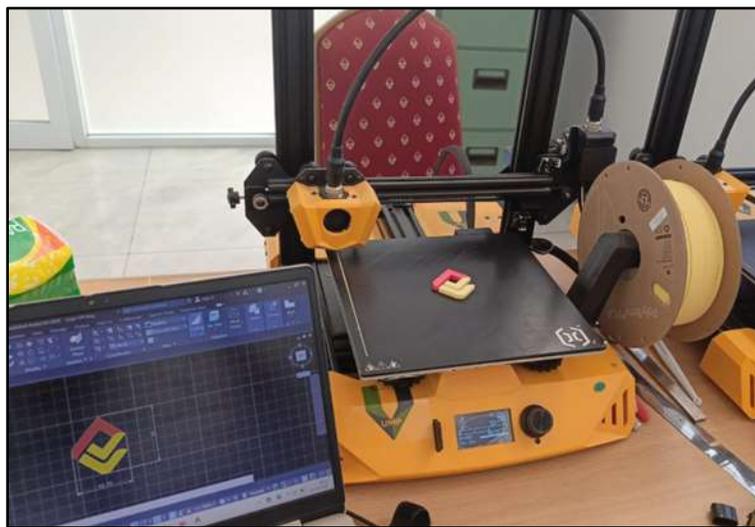


Figure 1 Fused Deposition Modelling

This initiative encompassed a structured capacity-building workshop aimed at strengthening participants' technical competencies and deepening their understanding of contemporary design and production practices. The workshop sessions (Figure 2) combined theoretical instruction with interactive discussions, enabling participants to engage critically with concepts related to sustainable materials, digital fabrication, and product development strategies. Particular emphasis was placed on fostering analytical thinking and problem-solving skills, ensuring that participants could contextualize new knowledge within their existing craft practices.



Figure 2 Workshop Session 1

In parallel, a series of design mentoring sessions was conducted to provide individualized guidance and constructive feedback. Experienced mentors worked closely with participants to refine design concepts, address technical challenges, and enhance aesthetic coherence. These sessions created a collaborative learning environment in which ideas could be tested, questioned, and progressively improved (Figure 3). Mentoring also supported participants in aligning their creative outputs with market expectations, encouraging responsiveness to evolving consumer preferences and environmental considerations.



Figure 3 Workshop Session 2

Hands-on prototyping formed a central component of the program, allowing participants to translate conceptual ideas into tangible products (Figure 4). Through iterative experimentation, they explored material properties, assessed functional performance, and identified opportunities for design optimization. This experiential approach not only reinforced theoretical knowledge but also built confidence in applying new techniques within real-world production contexts. By integrating capacity building, sustained mentoring, and practical prototyping, the initiative promoted meaningful skill development and facilitated the gradual adoption of more innovative and sustainable production practices.



Figure 4 Workshop Session 3

Local handicraft practitioners were systematically guided in adapting their existing crafting techniques to incorporate 3D printing technologies using polylactic acid (PLA) filaments. The initiative introduced participants to the technical fundamentals of additive manufacturing, including digital modeling, printer calibration, material preparation, and post-processing methods. Rather than replacing traditional skills, the program emphasized the integration of digital fabrication with established artisanal practices. This approach enabled craftspeople to retain the cultural and aesthetic value embedded in their work while enhancing precision, repeatability, and design flexibility through technological support.

Particular attention was given to the environmental advantages of PLA, a biodegradable thermoplastic derived from renewable resources. Participants were encouraged to consider the material's sustainability profile alongside its mechanical properties, surface finish, and compatibility with traditional craft materials such as wood, textiles, or natural fibers. Through guided experimentation, they explored hybrid production methods that combined hand-finishing techniques with 3D-printed components, thereby expanding the range of forms and structural possibilities available to them.

The incorporation of 3D printing also facilitated greater product customization. By learning to modify digital design files, artisans could adjust dimensions, patterns, and structural features to

meet specific client preferences without substantially increasing production time or material waste. This capability enhanced their responsiveness to evolving market demands for personalized and environmentally responsible products. Overall, the guided integration of PLA-based additive manufacturing strengthened local production capacity, fostered innovation, and supported the development of eco-friendly, customizable handicraft products while preserving the integrity of traditional craftsmanship.

At the end of the workshop series, participants were interviewed and surveyed to assess their understanding of the implementation of additive manufacturing in the production of sustainable, bio-based PLA for local handicraft applications. The evaluation process was designed to capture both the depth of conceptual knowledge and the extent of practical competence acquired during the training. Structured interviews allowed participants to reflect on their experiences, articulate perceived benefits and challenges, and describe how the newly introduced technologies could be integrated into their existing craft practices. The questionnaire was based on knowledge within the following categories.

#### Design flexibility

Design flexibility in the additive manufacturing of sustainable, bio-based polylactic acid (PLA) products for local handicraft refers to the expanded capacity to create complex geometries, customized forms, and intricate surface details that would be difficult to achieve through conventional manual techniques. By utilizing digital design software and layer-by-layer fabrication processes, artisans can easily modify dimensions, patterns, and structural elements without significantly increasing production time or material consumption. This adaptability supports small-batch production and personalized design variations while maintaining consistency and precision.

#### Waste reduction

Waste reduction in the additive manufacturing of sustainable, bio-based polylactic acid (PLA) products for local handicraft production reflects a significant shift toward more resource-efficient fabrication practices. Unlike conventional subtractive methods, which often generate excess offcuts and material loss, additive manufacturing deposits material precisely where it is required through a controlled, layer-by-layer process. This targeted material application minimizes scrap generation and allows for accurate estimation of input quantities prior to production.

#### Ease of customization

Ease of customization in the additive manufacturing for local handicraft production highlights the capacity to tailor designs efficiently to specific user preferences and market demands. Through digital modeling software, artisans can modify dimensions, patterns, textures, and structural features with precision, without requiring substantial changes to tools or production setups. This adaptability enables rapid adjustments to individual orders, facilitating personalized products while maintaining production consistency.

## Skill improvement of additive manufacturing

Skill improvement in the additive manufacturing of sustainable for local handicraft production represents a meaningful expansion of artisans' technical and analytical capabilities. These competencies complement established manual crafting techniques, fostering a hybrid skill set that integrates traditional craftsmanship with contemporary fabrication methods.

## Results and Discussion

Results from the implementation demonstrate that the integration of AM technology significantly enhances design flexibility while contributing to improved environmental performance through more efficient material use. The adoption of AM enabled producers to explore complex geometries and intricate design features that would be difficult or impractical to achieve using conventional fabrication techniques. This expanded formal vocabulary allowed for greater experimentation in product development, encouraging innovation without substantially increasing production time or cost.

In addition to broadening design possibilities, the integration of AM technologies supported more sustainable production practices. Because additive manufacturing builds objects layer by layer, material is deposited only where required, thereby reducing excess consumption and limiting offcuts commonly associated with subtractive processes. The precision of digital modeling further enabled accurate estimation of material quantities prior to fabrication, minimizing trial-and-error waste. As a result, overall resource efficiency improved, aligning production practices more closely with principles of environmental sustainability.

The results of the survey conducted among 12 handicraft MSME participants indicate that the integration of additive manufacturing technologies was positively received. A majority reported improved understanding of sustainable PLA materials, enhanced design flexibility, and increased confidence in applying digital fabrication techniques within their localized production practices.

From the survey and according to the participants, design flexibility increased by 14% compared to traditional manufacturing method. Following the adoption of additive manufacturing technologies. This improvement reflects the enhanced capacity to modify and adapt product designs using digital modeling and layer-by-layer fabrication processes. Unlike conventional production techniques, which often impose constraints on geometric complexity and tooling requirements, additive manufacturing enables rapid adjustments to form, dimensions, and structural features without significant reconfiguration of equipment. The observed increase demonstrates a shift toward more adaptable and responsive production practices.

Based on the survey findings and participants' responses, waste reduction decreased by 7% compared to traditional manufacturing methods when production was carried out using additive manufacturing with polylactic acid (PLA). This reduction reflects the material efficiency inherent in layer-by-layer fabrication processes, where raw material is deposited only in areas required for the final product. In contrast to conventional subtractive techniques, which often generate excess offcuts and scrap, additive manufacturing enables more precise control over material input and

output. The measured decrease in waste demonstrates improved resource utilization and supports environmentally responsible production practices within localized handicraft manufacturing systems.

According to the survey results as reported by the participants, ease of customization increased by 12% compared to traditional manufacturing methods following the adoption of additive manufacturing technologies. This improvement reflects the greater capacity to modify design parameters efficiently through digital modeling tools, enabling rapid adjustments to dimensions, patterns, and structural configurations without extensive tooling changes. Unlike conventional production processes, which often require time-consuming reconfiguration to accommodate variations, additive manufacturing supports flexible adaptation with minimal disruption to workflow. The recorded increase indicates enhanced responsiveness to individualized customer preferences and small-batch production demands, thereby strengthening the competitiveness and market adaptability of localized handicraft enterprises integrating sustainable manufacturing practices.

As indicated by the survey responses provided by the participants, skill improvement increased by 7% compared to traditional manufacturing practices following the adoption of additive manufacturing technologies. This measurable enhancement reflects the development of new technical competencies related to digital modeling, printer calibration, and material optimization using polylactic acid (PLA). Unlike conventional production methods that rely primarily on manual techniques, additive manufacturing requires familiarity with software-driven design processes and equipment management. The observed increase indicates that participants not only adapted to these technological tools but also strengthened their overall production capabilities.

The implementation also revealed improvements in process consistency and product quality. Digital workflows facilitated standardized production parameters, reducing variability across batches while maintaining the option for customization when required. This balance between uniformity and adaptability proved particularly valuable in responding to evolving market expectations for personalized yet environmentally responsible products. Collectively, these findings suggest that the incorporation of AM technologies not only expands creative and technical capabilities but also strengthens the environmental and economic resilience of localized manufacturing systems.

## Conclusion

The findings of this study demonstrate that the integration of additive manufacturing (AM) technology into local handicraft production yields measurable technical, environmental, and economic benefits. The observed 14% increase in design flexibility confirms that digital modeling and layer-by-layer fabrication substantially expand creative possibilities beyond the constraints of traditional manufacturing methods. Artisans were able to modify geometries, dimensions, and structural features with greater precision and responsiveness, enabling more adaptive and market-oriented production. Environmental performance also improved, as evidenced by the 7% reduction in material waste when using polylactic acid (PLA) in additive processes. This outcome reflects the inherent efficiency of AM systems, which deposit material only where necessary, thereby

limiting excess consumption and reducing scrap generation. The improved resource utilization aligns closely with sustainable production principles and reinforces the environmental value of localized fabrication. Moreover, the 12% increase in ease of customization and the 7% improvement in technical skills indicate meaningful capacity development among participants. The ability to implement digital tools confidently while maintaining craft identity suggests that AM can complement rather than replace traditional practices. Enhanced process consistency and product quality further strengthen the competitiveness of micro and small enterprises. Overall, these results confirm that additive manufacturing contributes to greater innovation, sustainability, and resilience within localized handicraft production systems.

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### References

- Assunção, J., Chadha, K., Vasey, L., Brumaud, C., Escamilla, E. Z., Gramazio, F., ... & Habert, G. (2024). Contribution of production processes in environmental impact of low carbon materials made by additive manufacturing. *Automation in Construction*, 165, 105545. <https://doi.org/10.1016/j.autcon.2024.105545>
- Feroz, A. K., Zo, H., & Chiravuri, A. (2021). Digital transformation and environmental sustainability: A review and research agenda. *Sustainability*, 13(3), 1530. <https://doi.org/10.3390/su13031530>
- Ghaffar, S. H., Corker, J., & Fan, M. (2022). Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Automation in Construction*, 141, 104403. <https://doi.org/10.1016/j.autcon.2022.104403>
- Gupta, S., Bag, S., Modgil, S., de Sousa Jabbour, A. B. L., & Kumar, A. (2022). Examining the influence of big data analytics and additive manufacturing on supply chain risk control and resilience: An empirical study. *Computers & Industrial Engineering*, 172, 108629. <https://doi.org/10.1016/j.cie.2022.108629>
- Jayawardane, H., Davies, I. J., Gamage, J. R., John, M., & Biswas, W. K. (2023). Sustainability perspectives—a review of additive and subtractive manufacturing. *Sustainable Manufacturing and Service Economics*, 2, 100015. <https://doi.org/10.1016/j.smse.2023.100015>
- Joseph, T. M., Kallingal, A., Suresh, A. M., Mahapatra, D. K., Hasanin, M. S., Haponiuk, J., & Thomas, S. (2023). 3D printing of polylactic acid: recent advances and opportunities. *The International Journal of Advanced Manufacturing Technology*, 125(3), 1015-1035. <https://doi.org/10.1007/s00170-022-10704-0>

- Klerkx, L., & Begemann, S. (2023). Supporting food system transformation: The role of innovation ecosystems and digital technologies. *Environmental Innovation and Societal Transitions*, 46, 74–87. <https://doi.org/10.1016/j.eist.2023.01.002>
- Kokare, S., Oliveira, J. P., & Godina, R. (2023). Life cycle assessment of additive manufacturing processes: A review. *Journal of Manufacturing Systems*, 68, 536–559. <https://doi.org/10.1016/j.jmsy.2023.05.007>
- Lang, L. D., Behl, A., Phuong, N. N. D., Gaur, J., & Dzung, N. T. (2023). Toward SME digital transformation in the supply chain context: the role of structural social and human capital. *International Journal of Physical Distribution & Logistics Management*, 53(4), 448–466. <https://doi.org/10.1108/IJPDLM-12-2021-0525>
- Müller, J. M., Buliga, O., & Voigt, K.-I. (2022). The role of Industry 4.0 in SMEs: Digitalization, sustainability and performance implications. *Technological Forecasting and Social Change*, 179, 121628. <https://doi.org/10.1016/j.techfore.2022.121628>
- Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., & Tortorella, G. (2022). Exploring Industry 4.0 technologies to enable circular economy practices in manufacturing systems. *Journal of Manufacturing Technology Management*, 33(2), 323–346. <https://doi.org/10.1108/JMTM-03-2021-0105>
- Peng, T., Kellens, K., Tang, R., Chen, C., & Chen, G. (2023). Sustainability of additive manufacturing: A critical review and future research agenda. *Journal of Cleaner Production*, 384, 135531. <https://doi.org/10.1016/j.jclepro.2022.135531>
- Ponis, S., Aretoulaki, E., Maroutas, T. N., Plakas, G., & Dimogiorgi, K. (2021). A systematic literature review on additive manufacturing in the context of circular economy. *Sustainability*, 13(11), 6007. <https://doi.org/10.3390/su13116007>
- Scipioni, S., Russ, M., & Niccolini, F. (2021). From barriers to enablers: The role of organizational learning in transitioning SMEs into the circular economy. *Sustainability*, 13(3), 1021. <https://doi.org/10.3390/su13031021>
- Singh, S., Ramakrishna, S., & Singh, R. (2022). Material issues in additive manufacturing: A review for sustainable applications. *Materials Today Sustainability*, 18, 100131. <https://doi.org/10.1016/j.mtsust.2022.100131>
- Troise, C., Corvello, V., Ghobadian, A., & O'Regan, N. (2022). How can SMEs successfully navigate digital transformation? *Journal of Business Research*, 146, 403–415. <https://doi.org/10.1016/j.jbusres.2022.03.016>
- Wang, X., Jiang, M., Zhou, Z., Gou, J., & Hui, D. (2022). 3D printing of polymer matrix composites: A review and prospective. *Composites Part B: Engineering*, 110, 442–458. <https://doi.org/10.1016/j.compositesb.2022.110458>
- Wiberg, A., Persson, J., & Ölvander, J. (2019). Design for additive manufacturing—a review of available design methods and software. *Rapid Prototyping Journal*, 25(6), 1080–1094. <https://doi.org/10.1108/RPJ-10-2018-0262>