

# Innovative Pathways in Leather Industry: A Comprehensive Review of Sustainable Technologies and Strategies

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The leather industry has undergone substantial transformations due to technological innovations, fostering more sustainable and efficient production methods. Several studies have been reported on innovative technologies and strategies employed in this industry so far. Despite the available literature in the field, a thorough analysis that summarizes and evaluates the recent advances in those innovations is still in its infancy. This review aims to provide an extensive overview of the latest developments in innovative technologies utilized in the leather industry. The findings from the literature indicate that technologies such as nanotechnology, artificial intelligence, augmented reality, additive manufacturing, and total quality management are at the forefront of this evolution. These state-of-the-art technologies have significantly transformed traditional production methods, addressing pressing environmental and sustainability challenges. Overall, these innovations have enabled manufacturers to enhance their business performance while addressing ecological and sustainability concerns at the same time.

**Keywords:** Automation, Eco-efficiency, Innovative technologies, Sustainability, Sustainable leather

## Introduction

The leather industry is a significant contributor to the global economy, with a global trade value surpassing 80 billion dollars annually.<sup>1</sup> The industry is experiencing a continuous paradigm shift due to environmental impact concerns, market dynamics and sustainability issues. As a resource-intensive process that consumes large quantities of water and chemicals, leather manufacturing generates significant amounts of solid waste, wastewater, and air emissions. For instance, an average of 10–25 m<sup>3</sup> of water is consumed at various stages of leather making, resulting in the generation of 8–20 m<sup>3</sup> of wastewater, which could ultimately pose a serious risk to the environment if managed improperly.<sup>2</sup> In addition to these environmental concerns, the leather industry faces challenges from evolving market dynamics and consumer preferences.<sup>3,4</sup> Consumers today are more conscious, demanding products that are not only fashionable and high-quality, but also sustainable and ethically manufactured.<sup>5</sup> Furthermore, the United Nations' Sustainable Development Goals (SDGs) have further galvanized the need for sustainability in the leather industry. Responsible

manufacturing and consumption (SDG 12) and climate action (SDG 13) are particularly relevant, calling for urgent action to combat climate change and its impacts.<sup>6</sup> Recognizing these challenges, the leather industry has witnessed a surge of innovation in recent years. Technological innovations including the adoption of automation technologies<sup>7</sup>, the development of biotechnology and sustainable practices<sup>8,9</sup>, and the implementation of advanced machinery have significantly impacted the performance of leather industry. Additionally, the integration of artificial intelligence (AI) and machine learning systems in manufacturing processes has enhanced the industry's productivity while reducing the risk of errors by up to 50%.<sup>(10)</sup> On the other hand, strategies such as just-in-time inventory management, employee training, and collaboration with suppliers and customers are being employed to streamline processes and reduce waste.<sup>11</sup> These technological innovations coupled with robust manufacturing strategies have made the leather-making process more environmental friendly and sustainable, which results in leather products with enhanced quality.<sup>12</sup> Furthermore, the industry is experiencing a period of change, particularly in marketing, with a focus on promoting the use of sustainable leather and educating the public about its beauty, quality, and versatility.

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Despite the overall significance of these innovative technologies, their implementation was highly impacted by challenges such as inadequate infrastructure and lack of skilled workforce in industries located in emerging nations.<sup>13</sup> In this context, as per the reports witnessed by the Global Innovation Index of 2020, innovative technologies in low-income countries account for 6% out of the 50 most innovative countries in the world.<sup>14</sup> Additionally, the global spending for research and development (R&D) of innovative technologies in emerging nations was insignificant, compared to the 79% budget allocated for R&D in developed countries.<sup>13</sup> In this regard, several studies have been reported on innovative technologies used in the leather sector. Despite the existing literature, there is a need for a comprehensive review that synthesizes the recent advancements in innovative technologies for improved efficiency in the leather industry along with the potential challenges associated with the adoption of each innovative technology and strategy. Herein, this review aims to provide an overview of these technological advancements employed to improve the overall performance of the leather industry.

### Methodology

All the data and information were systematically evaluated, to organize this review article. This paper was based on a systematic review of 101 papers on the latest developments in innovative technologies utilized in the leather industry which were found in relevant journals. The applicable sources obtained from digital libraries were books, articles and conference proceedings. The initial stage of the systematic literature review process involved the use of several databases, including Science Direct, Google Scholar, Elsevier and Springer. The search was conducted by combining keywords including “leather processing”, “innovation/leather”, “innovative technology/leather”, “innovative technology/ footwear”, “sustainability/footwear”, “nanotechnology/ leather”, “bioleather”, “automation/leather”, “augmented reality/footwear”, “additive manufacturing/ footwear”, “total quality management/footwear”, “bioleather”, “sustainable leather”, “biotechnology/leather”, and “footwear and diabetics”. To ensure a particular degree of quality, the review process was restricted to peer-reviewed publications and predatory papers were disregarded. Peer-reviewed publications from scholarly journals published between 2009 and 2024

were chosen. There have been 170 relevant articles in total as a consequence of this approach. The articles which featured a call for papers or had a focus other than innovative technologies and strategies were not processed further. Hence, innovative technologies and strategies for improved efficiency in the leather industry remained the focus of the review assortment. The most relevant articles were gathered in the second stage based on their relevancy in terms of title, abstract, and contents and irrelevant and duplicated results were removed. The third stage involved carefully reading and evaluating the abstracts of the remaining 125 publications to determine their applicability. The authors were able to differentiate relevant publications and those that weren't by looking more closely at their abstracts. Finally, 101 articles were taken for in-depth examination and analysis in the final phase. All the collected information and data were analyzed for writing this review article systematically. The general procedure followed to articulate this review paper was presented schematically as follows in Fig. 1.

### Distribution of Research Publications in the Leather Industry

Through systematic categorization, the publications are grouped into different topic areas such as innovations by nanotechnology, biotechnology, artificial intelligence, industrial automation, augmented reality, sustainable practices and so on. Quantitative analysis is performed to determine the distribution of publications across these topics. Additionally, a qualitative analysis is conducted within each category to identify trends, key findings, and research gaps. The results are synthesized into a comprehensive research review, providing insights into the current state of research and suggesting future research directions. The overall topic-wise distribution of the paper is summarized in Fig. 2.

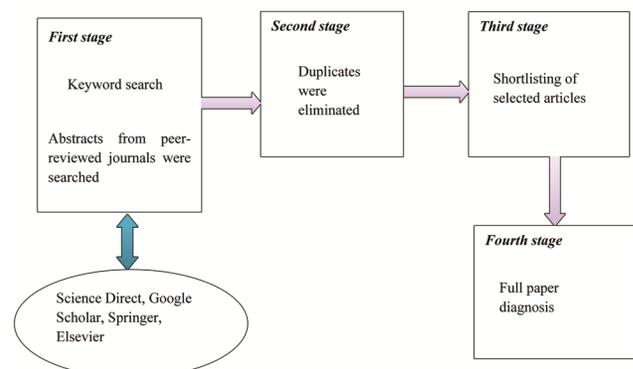


Fig. 1 — Methodology followed for this review

## Findings and Discussion

### Sustainable Leather Processing

The leather industry is increasingly focusing on sustainable practices to alleviate environmental impact via incorporating innovative technologies and strategies and environmentally friendly processing methods. This has resulted in the development of novel materials and technologies for sustainable production, such as eco-leather and chromium-free tanning agents.<sup>1,15,16</sup> Biotechnology is among the aspects by which the sustainability issue of leather is optimized to a great extent nowadays. As such, it is being increasingly explored for sustainable leather processing, offering potential benefits including reduced environmental impact and animal-friendly alternatives such as cactus, mushroom, and pineapple leather-like materials.<sup>17</sup> For instance, enzymes obtained from biotechnological processes can be applied in various steps of leather production, including soaking<sup>18,19</sup>, unhairing<sup>20</sup>, bating, dyeing<sup>21</sup>, and

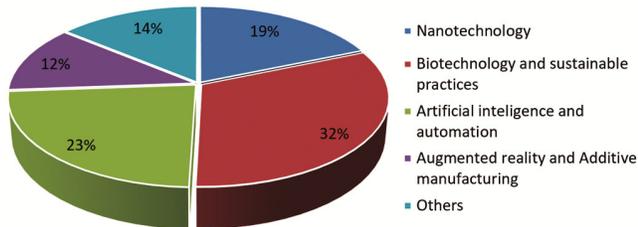


Fig. 2 — Topic-wise distribution of publications on innovative technologies

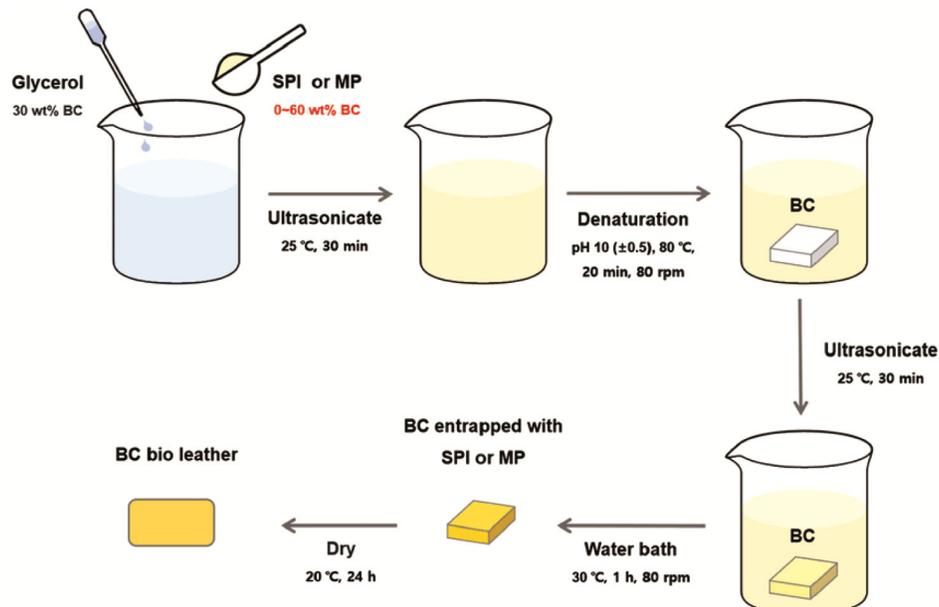


Fig. 3 — Fabrication of leather-like materials from bacterial cellulose via biotechnological pathway<sup>27</sup>

degreasing, as well as in the treatment of effluent and solid wastes<sup>22</sup> for achieving better quality products and more sustainable processes in the industry. This strategy seeks to reduce the leather industry's usage of hazardous chemicals, water, and waste disposal. Additionally, researchers have been exploring different methods to produce leather-like material, using microbial biotextiles<sup>23</sup>, plant-based materials like pineapples<sup>24</sup>, mushrooms<sup>25</sup>, tissue engineering<sup>26</sup>, and bacterial cellulose as indicated in Fig. 3. These approaches aim to reduce the environmental impact and human toxicity associated with traditional leather manufacture.

For instance, microbial biotextiles have been shown to have thousand fold reductions in human toxicity levels compared to cow leather.<sup>23,28</sup> The growing need for eco-friendly and sustainable alternatives has led to increased attention and investment in the development of bio-leather, making it a promising solution for the fashion, furniture, and automotive industries.<sup>29</sup> Various bio-materials obtained from sources such as mycelium<sup>30</sup>, plant<sup>25</sup>, and tissue engineering<sup>26</sup>, have been explored in the bio-based leather market. Vegan leather is a sustainable alternative made from plant-based materials such as pineapple leaves, cactus leaves, mushroom mycelium, coconut fibres, and cork oak bark.<sup>31</sup> These materials are more sustainable than traditional animal-based leather and synthetic leather made from petroleum-based plastics like PVC and PU.<sup>32,33</sup> Additionally, innovative processes have been

developed to recycle leather waste and create biodegradable and recyclable bio-leather materials.<sup>34</sup> These developments in biotechnology research highlight the possibility of sustainable leather substitutes for conventional leather. However, these biotechnologically fabricated leather-like materials are not immune to various obstacles confronting such growing companies. In this context, while these materials have some physical and mechanical properties that make them suitable for replacing conventional leather, a review of the available information shows that they fail to meet the minimum standards for many important material attributes. For example, despite the remarkable robustness of *Schizophyllum commune's* mycelium in strength, it has been noted that this biomaterial falls short in terms of durability, flexibility, and resistance to both biological and chemical deterioration as compared to traditional materials.<sup>35</sup> Additionally,

modifying mycelium to enhance properties like comfort, durability, flexibility, and ease of cleaning is necessary. Hence, the inclusion of these considerations enhances the overall understanding of the complexities and limitations associated with the adoption of such technologies in the leather industry. The advantages of innovative processes over conventional approaches have been depicted in Table 1. An innovative process is those consisting of a series of strategic actions characterized by the adoption of novel and creative methods, aimed at accomplishing specific organizational objectives within a defined timeframe.<sup>36</sup> Hence, the leather industry is undergoing a significant transformation, driven by the need for more sustainable and environmentally friendly practices. In order to raise the overall sustainability performance and the quality of leather goods, a number of novel processes are currently being developed.

Table 1 — Comparison of conventional and innovative technologies in leather industry

Processing stage	Conventional methods	Innovative processes
Preparatory	Soaking hides in large vats of water for extended periods leading to high water consumption and waste. Manual removal of hair.	Introduction of enzymatic or biological processes for more efficient and eco-friendly processing. Adoption of automated machinery for flesh removal such as hydraulic fleshing machines (used for cow hides and sheep skins, utilizing hydraulic power for effective flesh removal) and fleshing disk machines (machines that employ a rotating disk blade to flesh mink and sable skins, ensuring a thorough and uniform removal of flesh).
Tanning	A conventional tanning method involving the use of chrome salts poses environmental concerns due to toxic waste generation. Lengthy and process-intensive processes.	Development of alternative tanning methods such as chrome-free tanning methods such as zeolite tanning (an innovative approach that utilizes zeolite minerals, which can absorb and release water depending on temperature). Zeolite tanning maintains the performance characteristics of leather while reducing environmental pollution associated with traditional tanning methods. <sup>37</sup> Implementation of accelerated tanning techniques such as accelerated chromium sulphate complexation (a method that utilizes basic chromium sulphate in a high-pressure environment to speed up the tanning process) <sup>38</sup> , ultrasound and microwave-assisted tanning (an innovative approach combines ultrasonic waves and microwave energy to accelerate the chrome tanning process) <sup>39</sup> , carbon dioxide (CO <sub>2</sub> ) intensified tanning (a method that utilizes compressed CO <sub>2</sub> to facilitate the tanning process) <sup>40</sup> to reduce processing time and resource consumption.
Crusting	Traditional methods involve the use of synthetic chemicals and high energy consumption. Limited control over the quality and consistency of the leather.	Adoption of eco-friendly biodegradable chemicals in the crusting process, minimizing environmental impact. Integration of advanced technologies for precise control over parameters resulting in improved leather quality and uniformity.
Surface coating	Utilization of solvent-based coatings leads to VOC emissions and environmental pollution. Limited durability and performance of coatings.	Introduction of water-based or solvent-free formulations reducing VOC emissions and improving environmental sustainability. Development of sustainable coating techniques such as plasma or nanotechnology-based coatings enhancing durability and performance.

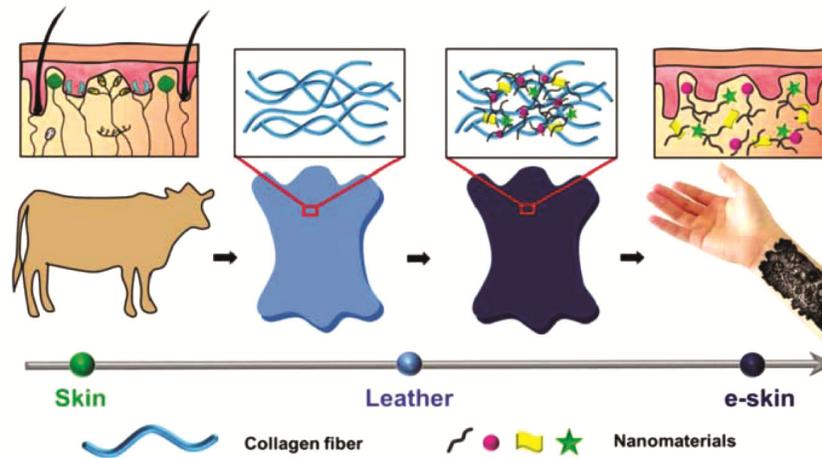


Fig. 4 — Role of nanomaterials for fabricating conductive leather

### Nanotechnology

Nanotechnology has been increasingly explored for cleaner and more efficient leather processing. As such, it offers several advantages for leather processing over conventional methods.<sup>12,41</sup> Research has shown that nanomaterials and nanoscale applications can improve the quality of leather and the tanning process, leading to the development of leather with enhanced properties at the nanoscale, such as antibacterial<sup>42</sup>, flame-retardant<sup>43</sup>, and self-cleaning properties.<sup>44</sup> As indicated in Fig. 4 such nanomaterials can also be used for fabricating conductive leathers. Moreover, nanomaterials, such as nano-oxides, polymers, and metals, have revealed potential advantages to replace chemicals in various stages of leather manufacturing including unhairing<sup>45</sup>, tanning<sup>41</sup>, retanning<sup>45</sup>, fatliquoring<sup>46</sup>, dyeing<sup>45</sup>, and finishing<sup>41</sup>, leading to a more eco-friendly and effective process. In this context, these nanomaterials can enhance the properties of leather, including its durability, stain resistance, and water repellency. Additionally, nanomaterials can provide more efficient use of chemicals, reducing their consumption and environmental impact.

The advancement of nanotechnology has also created new avenues for the treatment of industrial effluents, such as wastewater from tanneries. Nano technological routes are more effective than their traditional equivalents, due to their higher surface area to volume ratio and better chemical characteristic.<sup>47</sup> Nanomaterials have many advantages over conventional materials for treating tannery wastewater because of their large surface area relative to their volume, and high reactivity.<sup>48</sup> Nanomaterials, such as magnesium oxide nanoparticles, magnetite

nanoparticles, and silica nanoparticles, were used for tannery effluent remediation. For instance, the use of algae nanotechnology has been studied for tannery wastewater remediation and efficiency in heavy metal elimination, offering potential solutions for the environmental impact of leather manufacturing.<sup>49</sup> The findings revealed the potential of nanotechnology to address environmental issues facing the leather sector. These advancements in nanotechnology could improve the quality of leather and contribute to the reduction of environmental impact in the leather industry. Herein, the use of nanotechnology in leather production holds the potential for increased efficiency and sustainability. However, safety considerations regarding the use and handling of nanoparticles need to be addressed to ensure worker and consumer safety. The scalability and cost-effectiveness issue of nanotechnological applications is also another constraint that should be addressed via further exploration and optimization.

### Artificial Intelligence

Artificial Intelligence (AI) refers to the ability of machines, particularly computer systems, to simulate human intelligence processes.<sup>50</sup> It includes machine learning and deep learning sub-fields that are often discussed alongside artificial intelligence.<sup>51</sup> In recent years, artificial intelligence technology has grown faster, and many industries need to rely on this technology for transformation and upgrading.<sup>52</sup> Hence, this technology has been employed to optimize the production process<sup>53</sup>, enhance quality control<sup>54</sup>, and improve sustainability<sup>55</sup> in various industries. Additionally, problems in leather products, such as colour variances, surface imperfections, and

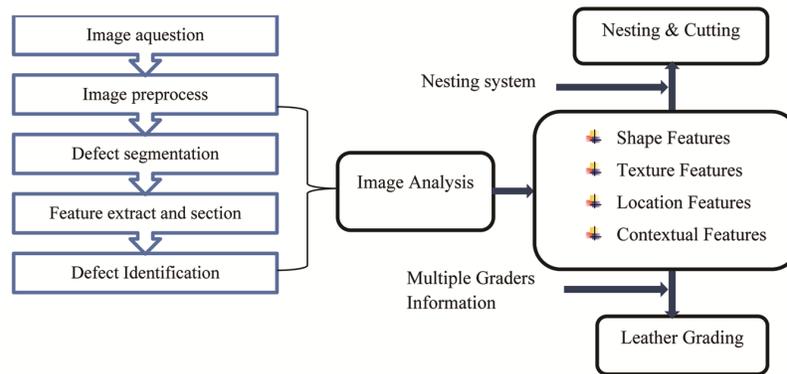


Fig. 5 — Vision-based automatic leather surface defect inspection system

stitching mistakes were detected via this technology.<sup>56</sup> Moreover, it can also be used to optimize the supply chain of the leather industry by assessing data on supplier performance and enhancing personalization and recommendation systems to customize leather goods for clients.<sup>57</sup> These systems may recommend strategies to minimize water and energy use and enhance the leather industry's sustainability via monitoring production data.

In a study conducted by Meria<sup>58</sup>, a deep learning network which is suitable for waste recognition generated in the leather industry was reported. Hence, an average accuracy of 0.8254 was revealed as a consequence of tool verification process. As such, the finding of the research witnessed that; the program can be used to detect waste of economic activity in the leather product industry and has a chance of being used as an established system for automatically identifying loss of economic activity. In another study, a fine-tuning transfer learning method was used to identify the kinds of leather flaws.<sup>56</sup> The findings showed that the suggested remedy was appropriate for differentiating the traits of these leather flaws. The mechanism by which the machine vision system detects a leather defect is highlighted in Fig. 5.

Additionally, automatic vision-based leather and stitching defect classification on leather surfaces were also reported.<sup>7</sup> These experimental findings collectively confirmed that the efficiency and the applicability of the intended approach are invaluable, showing high values of precision and accuracy. However, there are significant obstacles in the way of AI's successful use in the leather sector. One such significant challenge is the lack of a skilled workforce in the sector to work with AI systems. This is compounded by the lack of adequate infrastructure necessary to support AI technologies, particularly in emerging economies where the leather industry is prevalent.

### Industrial Automation

The introduction of automation and process control systems has allowed the leather industry to be more productive and sustainable while ensuring greater global competitiveness and extremely high quality of the finished article.<sup>59,60</sup> Accordingly, industrial automation has become a game-changer for leather manufacturers, allowing them to significantly improve their productivity, efficiency, and profitability. While the cost of implementing automotive technologies may vary depending on the specific needs of each factory<sup>61-63</sup>, their benefit in leather manufacturing is evident in consistent quality control, streamlined supply chains, and enhanced sustainability credentials. Table 2 shows how several cutting-edge technologies have impacted the leather industry's efficiency.

Automated cutting machines<sup>10</sup>, automated stitching machines<sup>64</sup>, robotic cells for handling and processing<sup>65</sup>, and automated material handling and transportation systems<sup>66</sup> have been some of the automotive technological innovations in the leather industry reported so far. For instance, automated cutting machines can be programmed to cut multiple layers of leather at a time, reducing the time and labour required for the cutting process.

On the other hand, different types of stitches and patterns can be made via programmed automated stitching machines which result in a reduction of manual labour requirements.<sup>64</sup> Additionally, the handling and processing of leather articles with industrial robots has been realized to ensure constant quality standards and manage production flows.<sup>67</sup> After all, automated material handling and transportation systems help in the movement of materials, finished products, and supplies, providing real-time updates on inventory levels and minimizing the chances of running out of stock and excessive inventory.<sup>66</sup> These technologies have revolutionized

Table 2 — Summary of some innovative technologies in the leather industry

Technology/Strategy	Description	Application in the Leather Industry	Impact on Efficiency
<i>Nanotechnology</i>	The use of nanoscale materials and processes in leather production	Improving leather strength, durability and water resistance; enhancing dye absorption and color fastness	Increased precision in production; Enhanced product quality
<i>Artificial Intelligence (AI)</i>	Implementation of AI systems for quality control, pattern recognition and process optimization	Automated defect detection, intelligent production planning	Improved accuracy and consistency, reduced production time and waste
<i>Automation</i>	Integration of automated machinery and robotics in leather manufacturing	Automated cutting, stitching, and finishing processes	Higher production speed, reduced labour costs
<i>Biotechnology</i>	Application of biological processes and materials in leather processing	Enzymatic treatments, bio-based tanning agents	Improved process efficiency, reduced chemical usage
<i>Sustainable materials</i>	Utilization of eco-friendly and renewable materials in leather production	Plant-based or recycled alternatives to traditional materials	Reduced carbon footprint, reduced dependence on non-renewable resources

the leather manufacturing industry by reducing the need for manual labour, increasing efficiency, and improving the quality and consistency of the final product. While the benefits of automation in terms of productivity, efficiency, and quality control are evident as per the literature, the cost of acquiring and implementing automated cutting machines, automated stitching machines, robotic cells, and automated material handling systems can vary depending on the specific needs of each business. This cost factor may present a challenge for some leather manufacturers, especially smaller businesses with limited financial resources, as they may struggle to afford the initial investment required for these technologies.

#### Total Quality Management

Total Quality Management (TQM) can be an innovative strategy for the leather industry, as it focuses on satisfying customer requirements with superior products qualities and services. Implementing a phase-based TQM framework and establishing quality control standards can help enhance leather product quality and make the sector more competitive in the global market.<sup>68</sup> By embracing TQM and staying up to date with the latest technological and innovative advancements, the leather industry can ensure the production of high-quality, competitive, and profitable products. Business success lies in the ability of a company to apply a quality system effectively to maintain the quality of its products and services at a relatively minimal cost. At various phases of manufacturing, the leather product sector has used a variety of quality management approaches.<sup>69</sup>

Some scholarly published research has been reported on the effect of TQM on leather product manufacturing firm's performance.

In a study conducted by Agbola and Ankrh<sup>70</sup>, five potential TQM practices were investigated to assess their effect on small and medium Enterprise's (SMEs) performance in Ghana including textile, leather product and footwear sectors. The fundamental TQM practices evaluated for their impact on performance included awareness of total quality management and the availability of a quality management policy. Additionally, these practices encompassed leadership commitment to quality, the adoption of new technology, ongoing quality improvement, enforcement of quality standards, and prioritizing customer satisfaction and needs. The outcome of the finding revealed that, of the SMEs selected as a case majority of leather garment industries have been aware of TQM. While 48% of leather SMEs is aware of TQM principles, only a few SMEs have written their quality policies in their businesses. On the other hand, a study by Oakland<sup>71</sup> suggested that one of the fundamental TQM activities is the formulation of a quality policy by the organization. However, most SME manufacturing sectors taken as a case have failed to incorporate quality policy as their business strategy and it has been discovered that just one company in the leather goods sector has a quality policy outlining the company's goals and mission for quality. Concerning the application of modern technology in those manufacturing firms, 54% of businesses in the subsector were textile and clothing industries. The

rationale behind this was that those industries were mature enough to accommodate the investment required for technology. Moreover, the majority of the case leather product sectors agreed positive effect of leadership commitment to enhance the quality of their products.

In another research carried out in Bangladesh's leather sector, Key Performance Indicators (KPIs) concerning the quality of leather product industries for operational excellence were reported.<sup>72</sup> Operational excellence can be used interchangeably with TQM as it refers to the ongoing advancements made by different industries inside their ecosystem to attain a competitive advantage. The results indicated that the most important KPIs in the management group are those related to effective inventory management, competent capacity utilization leadership, and manufacturing tracking system control. Additionally, recent research on the leather product industry in Indonesia identified several key factors that could serve as potential KPIs relevant to total quality management. These include the utilization of information technology for marketing products, the implementation of advanced technology in production processes, financial and capital structure considerations, as well as market and entrepreneurial orientation.<sup>73,74</sup> Additionally, product designs were modified to meet customer needs. The participants asserted that they handled complaints with care and made necessary adjustments until the items satisfied the buyer's expectations. In this sense, the potential of implementing TQM throughout the leather business and establishing quality control standards for enhanced competitiveness in the global market has been pronounced. On the other hand, limited adoption of TQM practices and quality policies has been revealed by SMEs in the leather product industry. This limited adoption of TQM in SMEs may be attributed to the lack of awareness, resources, and understanding of TQM principles and their potential benefits.<sup>75</sup> Herein, the leather industry, particularly those SMEs, should focus on integrating TQM practices more effectively into their operations via developing and implementing quality policies that align with their business strategies, emphasizing leadership commitment to quality, and fostering a culture of continuous improvement.

#### **Additive Manufacturing and Augmented Reality**

The footwear industry is a diverse sector that produces garments worn on the feet, primarily for protection against environmental adversities such as wear from rough surfaces, cold, dampness, dust, heat,

and roughness of the ground.<sup>76</sup> The industry has evolved, with advancements in materials, production processes, and design trends. The global footwear market is significant, with the Asia-Pacific region holding a prominent share.<sup>77</sup> Accordingly, the global market size is projected to increase from USD 390.10 billion in 2023 to USD 503.83 billion by 2028, reflecting a compound annual growth rate (CAGR) of 5.25%. Innovative technologies are revolutionizing the footwear industry across various fronts, driving advancements in production efficiency and product customization. The emergence of state-of-the-art technologies has reshaped the footwear landscape, with innovations such as smart shoes with embedded sensors and connectivity features that provide real-time feedback on performance metrics and self-lacing capabilities.<sup>78</sup>

Additive manufacturing (3D printing) and augmented reality (AR) are the two most innovative technological advances in the footwear sector reported so far.<sup>79,80</sup> Additive manufacturing has been increasingly integrated into the footwear industry<sup>81</sup>, revolutionizing the way shoes are designed and manufactured. The process of 3D printing involves foot scanning, data input, design and customization, 3D printing, and post-processing for sanding and painting to achieve the final look.<sup>82</sup> This technology offers several benefits, including the ability to create intricate designs, customize shoes for a perfect fit, and reduce production costs.<sup>83</sup> Furthermore, the technology has the potential to significantly reduce waste and improve the sustainability of shoe production, as well as to enable mass customization and personalized footwear.<sup>84</sup> As a result, the footwear industry is increasingly embracing 3D printing as a way to drive innovation and address various challenges in traditional manufacturing processes.

Augmented reality is a technology that superimposes virtual features on the actual environment, resulting in an immersive and interactive experience, as mentioned in Fig. 6. It has various applications in the design and production process in the leather product industry. One of the applications of AR is in product validation before manufacturing. By using AR, designers and customers can visualize and validate virtual prototypes of products in a real-world context. This can help identify design flaws or potential issues before investing in physical manufacturing, saving time and resources.<sup>85</sup> AR can also facilitate tasks by providing real-time guidance and instructions. For example, in manufacturing processes, workers can use



Fig. 6 — Application of augmented reality in the footwear sector

AR headsets or gadgets to get detailed instructions, decreasing mistakes and boosting efficiency.<sup>86</sup> In terms of employee training, AR can simplify the learning process for new employees. By overlaying digital information or virtual guides onto the physical workspace, AR can provide interactive and guided instructions, helping new employees quickly understand and perform their tasks.<sup>85</sup> Furthermore, AR can be used to enhance the shopping experience for end-users. Customers can use AR applications or devices to try on shoes or other clothing items virtually. Hence, through overlaying virtual products onto the real world, customers can see how the items look and fit before making a purchase decision.

This interactive shopping experience can increase customer engagement, promote brand recognition, and potentially lead to increased revenue.<sup>85</sup> In this context, AR technologies are driving the leather industry towards sustainability, customization, and global market expansion. Leveraging AR in various stages of the design, production, and sales processes, can improve efficiency, reduce costs, and provide enhanced experiences for both employees and customers in the footwear sector.

#### **Impact of Innovative Technologies on the Future of the Leather Industry**

The future of the leather industry is being shaped by innovative technologies and strategies that aim to combine traditional methods with modern advancements. These changes driven by factors such as sustainability<sup>86</sup>, smart technologies<sup>87</sup>, digital transformation<sup>88</sup>, and innovative production processes<sup>89</sup> apart from others can create a new paradigm shift on the future of the industry. From automated monitoring systems to AI-driven quality control, these advancements are revolutionizing the way leather is manufactured, ensuring precision and efficiency. For instance, the use of sustainable materials like pineapple and cactus leaves<sup>90</sup>, lab-grown leather<sup>26</sup>, mycelium<sup>91</sup>, and bacterial cellulose<sup>25</sup> as well as the development of innovative sustainable production methods like chrome-free

processes<sup>92</sup> will enhance the efficiency and ecological impact of leather industries. The global market for bio-based leather on the other hand is also projected to grow, indicating a shift towards environmentally friendly materials in the leather industry. Additionally, as consumer demand for environmentally friendly leather products grows, companies are increasingly motivated to adopt more sustainable practices, and those that embrace sustainable alternatives will be better positioned to meet the needs of their customers.

Artificial intelligence and smart technologies are impacting the future of the leather industry in several ways. While AI is being used to forecast trends<sup>93</sup>, optimize supply chains<sup>94</sup>, and understand consumer patterns<sup>95</sup>, smart technologies including IoT-integrated products and block-chain traceability, are enhancing transparency in the leather supply chain, ensuring product authenticity, and providing consumers with valuable insights into the bulk leather product making process.<sup>96</sup> Furthermore, the future of the leather industry is significantly impacted by innovative production techniques like automation and additive manufacturing. Automation technologies such as cutting-edge machinery, robotics, and artificial intelligence, can improve productivity<sup>97</sup>, efficiency and profitability<sup>98</sup> while reducing manufacturing costs and risks. Similarly, additive manufacturing technologies can produce complex geometries with a variety of materials in a relatively shorter period, which can be highly beneficial for the footwear and leather goods sector.<sup>99,100</sup>

Nanotechnology is another factor of interest that will significantly impact the future of the leather industry. Accordingly, its use aligns with the broader trend of incorporating advanced materials and technologies<sup>101</sup> to meet the evolving demands for sustainable and functional products. Its potential to enhance and embed new properties in leather for the development of smart and functional leather products has been explored on a wider scale recently. After all, by embracing these trends and adopting innovative technologies and strategies, the leather industry can future-proof itself and contribute to a more conscious and sustainable future.

#### **Conclusion and Remarks for Future Work**

This review underscores the potential of innovative technologies in modeling the future of the leather sector via enhancing efficiency and mitigating environmental impacts. As the industry faces growing regulatory pressures and rising consumer

awareness of sustainability, the integration of innovative technologies has become a matter of concern. The significance of these innovations extends beyond mere compliance as they represent a paradigm shift towards sustainable practices that align with contemporary consumer expectations. Collectively, in this evolving scenario, the future of leather industry appears promising for those willing to invest in sustainable technologies. On the other hand, while these advancements have brought about significant improvements, there are still potential research gaps that should be explored. Given the environmental challenges associated with conventional leather production, researches could be conducted on the exploration of more sustainable & eco-friendly leather-like materials with comparable physical properties with conventionally processed leathers. Additionally, further research could be undertaken on strategies to tackle the challenges in successfully implementing innovative technologies in the leather industry particularly in the context of emerging economies. After all, by addressing these potential research gaps, the leather industry can continue to advance and innovate, while meeting the growing demand for sustainable and high-quality leather products.

#### Data Availability

The review article contains all the information needed to support the findings of the review.

#### Conflicts of Interest

The authors state that they have no competing interests.

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