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Artificial Intelligence–Driven Life Cycle Sustainability Assessment of UV and UV-LED Printing Ink Technologies

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Abstract: The move towards sustainable manufacturing in the printing industry has really ignited interest in energy-curable ink technologies, particularly ultraviolet (UV) and ultraviolet light-emitting diode (UV-LED) systems. While UV-LED curing is often praised as a greener alternative to traditional mercury-based UV curing, comprehensive and data-driven assessments of its sustainability are still quite limited. This study presents an artificial intelligence (AI)–driven life cycle assessment (LCA) framework aimed at systematically evaluating and improving the environmental performance of both UV and UV-LED printing ink technologies. The framework utilizes machine-learning techniques for various tasks, including life cycle inventory (LCI) data collection, filling in gaps, modelling surrogate processes, predicting emissions, and optimizing decisions across multiple criteria. A comparative sustainability assessment is included, highlighting aspects like energy use, global warming potential (GWP), volatile organic compound (VOC) emissions, ozone depletion potential, and end-of-life risks. Insights from peer-reviewed studies and industry reports indicate that UV-LED curing can reduce energy consumption by around 60–80% compared to traditional UV systems, leading to significant cuts in greenhouse gas emissions. The integration of AI allows for rapid scenario analysis, improved uncertainty management, and informed decision-making, even when data is incomplete or proprietary. The study also tackles limitations, data quality concerns, and future research paths, underscoring the promise of AI-assisted LCA as a strategic tool for advancing sustainability in the printing and packaging industries.

Keywords: UV inks, UV-LED curing, life cycle assessment, artificial intelligence, machine learning, sustainability, printing technology, VOC emissions.

Introduction: The printing industry plays a vital role in global communication, packaging, and labelling, but it is also grappling with some serious environmental issues due to its heavy energy use, chemical reliance, and waste production. As regulations tighten, energy prices climb, and consumers grow more eco-conscious, printers are feeling the pressure to switch to cleaner, more efficient technologies. One exciting development in this area is energy-curable inks, particularly ultraviolet (UV) and ultraviolet light-emitting diode (UV-LED) inks, which are emerging as promising alternatives to the traditional solvent-based and water-based inks (Magdassi, 2009).

Traditional UV-curable inks rely on mercury arc lamps that emit broad-spectrum UV radiation to kick off the polymerization process in ink formulations. While these systems deliver quick curing and high quality prints, they consume a lot of energy and come with the downsides of mercury, ozone production, and significant heat output. In contrast, UV-LED curing systems use semiconductor diodes that emit narrow-band UV radiation, enabling instant on/off operation, lower temperatures, longer lamp lifespans, and eliminating the risks associated with mercury (Ink World, 2024).

Numerous reports and studies indicate that UV-LED systems can reduce electricity consumption by 60–80% compared to traditional UV curing systems under similar conditions. These operational advantages suggest considerable environmental benefits throughout the product's life cycle, especially in terms of energy use and greenhouse gas emissions. However, sustainability assessments that only consider energy savings during operation might overlook upstream impacts related to ink formulation, equipment manufacturing, and end-of-life management.

Life cycle assessment (LCA) is a well-known approach used worldwide to evaluate the environmental impacts of a product throughout its entire life span, starting from the extraction of raw materials all the way to its final disposal. Yet, in the printing industry, the application of LCA remains somewhat limited due to a variety of challenges. These include proprietary ink formulations, different substrates, fluctuating curing parameters, and incomplete inventory data (Aydemir, 2020). Such hurdles often create a lot of uncertainty, making it tough to effectively use LCA for industrial decision-making.

However, recent advancements in artificial intelligence (AI) and machine learning (ML) are opening up new avenues to tackle these issues. AI can streamline data processing, help fill in missing inventory information, model complex relationships in processes, and enable rapid scenario analyses (Romeiko et al., 2023; Wang et al., 2025). By merging AI with LCA, we can transform sustainability assessments from being just retrospective evaluations into proactive tools that enhance decision-making.

This study presents an AI-driven LCA framework specifically tailored for UV and UV-LED printing ink technologies. The objectives are to:

(i) Gather existing insights on the environmental performance of UV and UV-LED inks;
(ii) Develop an AI-assisted LCA methodology to address data gaps and uncertainties; and
(iii) Demonstrate, through specific indicators, how AI-enhanced LCA can support the selection and optimization of sustainable technologies in the printing industry.

2. Literature Review

2.1 Environmental Characteristics of Energy-Curable Inks: UV-curable inks are often regarded as low-VOC systems because they dry through a process called polymerization rather than relying on the evaporation of solvents. This characteristic has made them a go-to choice in regions with strict air quality regulations (Aydemir, 2020). However, there are still environmental concerns surrounding photo initiators, unreacted monomers, and additives that might pose health or ecological risks during their production, printing, or disposal. Moreover, traditional systems that use mercury-based UV lamps bring about additional environmental challenges, including hazardous waste and the potential for ozone formation. In contrast, UV-LED systems address many of these issues by eliminating mercury and reducing thermal stress, which can improve compatibility with substrates and minimize material waste.

2.2 Life Cycle Assessment of Printing Technologies: Life Cycle Assessment (LCA) studies in the printing industry have shown that energy consumption, raw material production, and waste management are significant contributors to environmental impacts. Aydemir (2020) emphasized that the energy involved in curing and the formulation of inks is vital in shaping the overall environmental footprint of printed products. However, there is a noticeable gap in comprehensive comparative LCAs between UV and UV-LED technologies, often stemming from challenges related to data confidentiality and variations in processes.

2.3 Machine Learning and AI in LCA: Machine learning is increasingly being used to support life cycle assessment (LCA) in a variety of fields, such as manufacturing, energy, and chemicals. As noted by Romeiko et al. (2023), machine-learning models can accurately replicate life cycle impact assessment (LCIA) results while significantly reducing computational time. Neupane et al. (2025) demonstrated that incorporating machine learning into LCA improves the completeness of inventory data and enables dynamic sustainability assessments, even when data is scarce. These findings highlight the crucial role of integrating AI into printing technologies, which often handle complex and proprietary datasets.

3. Research Methodology

3.1 Goal and Scope Definition: The goal of this study is to evaluate and compare how environmentally sustainable UV and UV-LED printing ink technologies are, using an AI-enhanced Life Cycle Assessment (LCA) framework. We are defining our functional unit as one square meter of printed substrate. The system boundary primarily focuses on the cradle-to-gate phase, but we are also taking a qualitative look at the end-of-life impacts related to ink residues and curing equipment. The impact categories we are examining include:

- Global warming potential (GWP)
- Cumulative energy demand
- VOC emissions
- Ozone depletion potential
- Generation of hazardous waste at the end of life

3.2 AI-Driven LCA Framework: The AI-LCA framework illustrated in Figure 1 is crafted to assess UV and UV-LED printing ink technologies. It brings together life cycle inventory (LCI) data collection, machine learning methods to enhance the data, life cycle impact assessment (LCIA), and multi-criteria decision support. This comprehensive approach is designed to bridge data gaps and minimize uncertainty in sustainability evaluations.

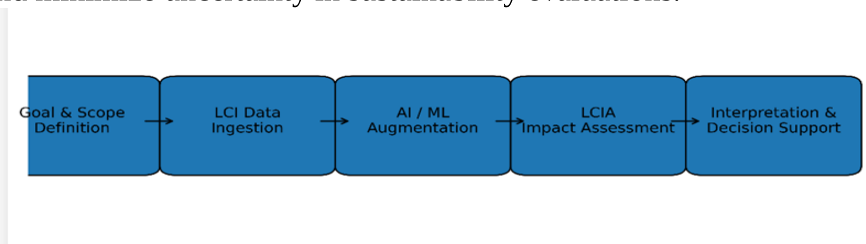

Figure 1. AI-driven life cycle assessment framework integrating machine learning for inventory augmentation, surrogate modeling, and decision optimization. (Adapted from concepts discussed in Romeiko et al. (2023) and Wang et al. (2025).)

3.3 Life Cycle Inventory Data and AI Augmentation: LCI collects information from a variety of sources, such as supplier technical datasheets, energy meters on production lines, VOC monitoring systems, lab analyses, and public databases. To address challenges with missing or uncertain data, we employ AI methods like random forests and gradient boosting to bridge inventory gaps, as well as neural networks to forecast curing energy and emission profiles under different operating conditions.

4. Illustrative Results: To show how this framework can be applied, we've gathered results from existing literature since we have limited access to proprietary industrial data. In Table 1, you'll find a summary of normalized environmental indicators, with conventional UV systems serving as the reference point (1.0).

Table 1. Illustrative normalized life cycle indicators (Conventional UV = 1.0)

Impact Category	**Conventional UV**	**UV-LED (Illustrative)**
Global Warming Potential	1.00	0.65
Energy Use	1.00	0.30
VOC Emissions	1.00	0.20
Ozone Depletion Potential	1.00	0.95
End-of-Life Hazard	1.00	0.80

The graph in Figure 2 shows how energy consumption varies during the curing processes for both conventional UV and UV-LED printing systems, with conventional UV serving as the baseline at 100. You'll notice that UV-LED curing uses a lot less energy. This efficiency comes from its ability to switch on and off instantly, its narrow-band emission, and reduced thermal losses.

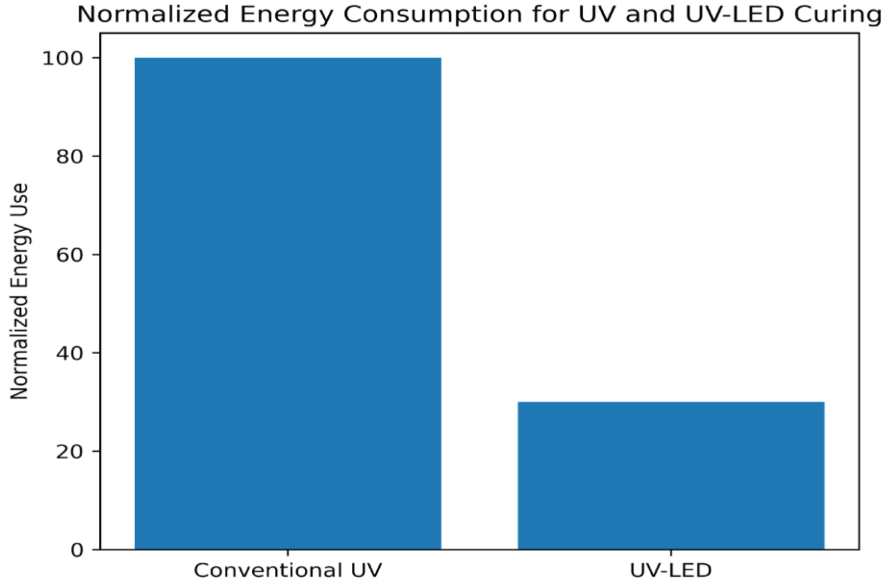

Figure 2. Normalized energy consumption for curing processes: conventional UV versus UV-LED. (Based on reported industry and literature ranges (Magdassi, 2009; InkWorld, 2024)

5. Result Discussion

5.1 Energy and Climate Impacts: One of the biggest environmental benefits of UV-LED systems is that they use less electricity. This drop in energy demand means fewer greenhouse gas emissions, particularly in power grids that depend a lot on fossil fuels. In addition, the fact that they can be

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turned on and off instantly boosts operational efficiency by cutting down on energy waste when they are not in use.

5.2 Emissions and Chemical Considerations: While UV inks are known for producing fewer VOC emissions than solvent-based systems, there are still some worries about leftover monomers and photo initiators. Using AI-driven predictive models can help estimate emission profiles based on the specific formulation and process parameters. This approach is useful for managing risks proactively, especially when direct measurements are not feasible.

5.3 Role of AI in Sustainability Decision-Making: AI is transforming Life Cycle Assessment (LCA) from just a basic evaluation into a robust optimization tool. It enables rapid assessments of various scenarios and helps analyze uncertainties, which ultimately leads to smarter decisions about technology options, process enhancements, and eco-friendly design. However, it is essential to ensure that AI models are clear and understandable to secure regulatory approval.

6. Conclusion: The blend of artificial intelligence and life cycle assessment creates a powerful and flexible approach to evaluating the sustainability of UV and UV-LED printing ink technologies. UV-LED systems bring notable environmental advantages, especially when it comes to energy efficiency and lower operational emissions. At the same time, AI methods enhance the reliability, speed, and relevance of life cycle assessments. This proposed framework not only encourages sustainable innovation but also sets the stage for data-driven environmental management in the printing industry.

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