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A gate-to-gate life cycle analysis of wide-format flatbed inkjet printing

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Short abstract

Life cycle analysis (LCA) studies of ultra-violet (UV) inks used for inkjet printing systems are an emerging field of research and development within the print and packaging industries. This study conducted a life cycle inventory analysis on four process UV light-emitting diode (LED) inks throughout the production of a plastic point-of-purchase (POP) display. Furthermore, this study considered the inventories of expendable consumable materials used for the set-up and cleaning processes of a wide-format flatbed inkjet printer and its total electricity consumption. The study found that electricity consumption from the wide format printing press contributed the most to human health, ecosystems, and resources endpoint indicators. Conversely, the UV LED inks' environmental contributions, and consumable inventory amounted to < 0.1, with most of the environmental impact stemming from the production of the polypropylene body of the lint-free microfiber cleaning swabs. In addition, the process contribution analysis per impact category indicated that the most significant environmental impacts contributed to (1) human health, global warming, (2) fine particulate formation, (3) human carcinogenics, and (4) human non-carcinogenics impact categories. The significant limitations of the study consisted of a lack of a controlled printing environment that affected ink consumption values. Likewise, this study only considered the environmental impact of the inkjet printer following the production of a plastic POP display. Hence, the results of this study are specific to the final product and its characteristics. This study also substituted ink ingredients based on relevant literature due to a lack of available inventories on SimaPro v9.0. Therefore, future studies are recommended to explore additional methods to model UV ink inventories, calculate ink consumption, and measure emissions for UV LED inks for multiple print applications. The study results further indicated that future research is needed to optimize the electrical consumption of inkjet printing systems to decrease environmental contributions.

Keywords: inkjet, ultra-violet ink, sustainability, LCA

1. Introduction and background

The graphic communications industry embraces ultra-violet (UV) curable ink technology as an environmentally sustainable alternative to traditional ink for many print and packaging applications. For example, UV ink technology provides applications for flatbed printers and novel applications in coating and labelling (Magdassi, 2009). The choice to adopt UV curable inks primarily lie within its function to remain as solid after curing processes and hence are affordable and energy-efficient (Magdassi, 2009). A significant research area of UV curable inks within the print industry includes the recent formulation of light-emitting diode (LED) UV ink technology for inkjet printing (Magdassi, 2009).

A variety of studies have been conducted on the environmental impacts of selected components of inkjet printing and UV ink printing, including a comparison of solvent-based, water-based, UV curable, and soy-based inks used in flexographic printing (Piluso, et al., 2009; Kozake, et al., 2021). In addition, a comprehensive review of typical formulas for UV printing inks is described in 'The Chemistry of Inkjet Inks' by Magdassi (2009) that states inkjet printing must be considered as a system to evaluate UV ink technology, such as the hardware, ink components, facility requirements (power). Furthermore, Piluso, et al. (2009) evaluated the environmental impact of an improved printing system (including UV curable ink) in comparison to several printing inks such as solvent-based and water-based inks. However, few life cycle assessment (LCA) studies have been conducted on Canada's UV inkjet printing system. Moreover, LCA studies focus on ink cartridge and toner-based ink printing systems (Pollock and Coulon, 1996; Kara, 2010; Krystofik, Babbitt and Gaustad, 2014), and solvent-based inks (Egawa and Kozake, 2019), but only finds a few recently published studies that analyze the impact of water-based solvents (Robert, 2015; Kawaguchi, et al., 2020), soy-based solvents (Tolle, et al., 2000), and UV ink technology (Piluso, et al., 2009; Liao, et al., 2012; Seipel, et al., 2018). This project aims to obtain a detailed life cycle inventory analysis and impact assessment of the UV LED flatbed digital printer system. This study uses a functional unit of UV ink (g), electricity (KWh), and other consumables (g) consumed for the digital printing of 10 000 plastic point-of-purchase (POP) products.

2. Materials and methods

This study conducted a LCA of a wide-format flatbed inkjet printing system in collaboration with an imaging and electronics company and a Toronto Metropolitan University-based creative technologies lab. This study complied with ISO 14040 and ISO 14044 (International Organization for Standardization, 2006a; 2006b) and used SimaPro v9.0, a LCA software, to model life cycle inventories and analyze their environmental impacts.

2.1. Goal and scope

The goals of this LCA were (1) to build a life cycle inventory for UV LED inks and (2) to analyze the environmental impacts of the intermediate processes involved in the inkjet printing of a plastic consumer packaged goods (CPG) point-of-purchase (POP) display (18-inch by 30-inch (457.2 mm by 762 mm)) using UV LED inks. In particular, the intermediate processes included raw material extraction and production of the UV inks, expendable consumables, and electricity consumption. First, the LCA began constructing a life cycle inventory for four UV bottle inks (CMYK) comprised of oligomers, monomers, photoinitiators, phenolic sensors, and additives based on primary data sourced from the ink manufacturer and secondary sources (Magdassi, 2009). Second, the LCA analyzed the environmental contribution of the ink, electricity, and expendable consumables using a gate-to-gate system boundary. Transportation and disposal were not considered for all inventories. The use of raw materials and processes to produce energy for the electricity consumption of the print system was not considered. The functional unit used for this study was the printing of 10 000 products. In Table 1, we see the material inventories under assessment.

2.2. Life cycle anventory analysis

2.2.1 CMYK UV inks

The first phase considers the raw materials and air emissions from the production of UV inks, consisting of oligomers, monomers, type I photoinitiators, and additives, as noted from primary and secondary sources. The goal of this inventory was to estimate the total amount of UV ink components, from a gate-to-gate perspective, for 10 000 products. Due to limitations of available inventories on SimaPro, the study substituted most ink components mentioned in the safety data sheets (SDS) as noted from secondary sources (Magdassi, 2009). However, this study used primary data to gather information about the POP product characteristics (e.g., substrate type, dimensions, ink percentage breakdown, ink coverage percentage), expendable consumables, and total time spent completing set-up procedures as noted from the structured interviews with the Toronto Metropolitan University-based lab. The specific ink ingredient and percentage of ingredients for each UV bottle ink inventory used the information listed on the corresponding SDS and was calculated using the formula below (Equation [1]).

$$\textit{Process Ink Consumption (g)} = \textit{Process Ink Weight} \times \textit{Material \%} \quad [1]$$

2.2.2 Expendable consumables used for set-up and cleaning

The second inventory considered the raw materials and intermediate processes used to produce the expendable consumables (see Table 1). The goal of this inventory was to estimate the consumption of the expendable consumables used for cleaning and maintenance, such as cleaning liquid, lint-free microfiber cleaning swabs, expendable plastic bags, and expendable nitrile gloves. Likewise, this inventory also considered the consumables to complete makeready materials, including painter's tape and recycled pulp paper, as observed from the Toronto Metropolitan University-based lab visitations. The cleaning materials were used once every 20 print runs, assuming the print runs are of average print size and ink consumption, whereas the makeready materials were used after each run.

At the beginning of each press run, the print operators use paper (recycled pulp) and painter's tape (Kraft Paper; Synthetic Rubber) to conduct a quality assurance test of the print nozzles and ink output. For cleaning and maintenance of the printer, cleaning solution (butyl diglycol acetate), lint-free cleaners (HDPE; polystyrene), expendable bags (LDPE) and gloves (LDPE) are used at the end of the printing process at end of every twenty runs.

2.2.3 Electricity consumption

The third inventory focused on the electricity consumption generated from the UV LED flatbed inkjet printer (see Table 1). The Toronto-based lab estimated the approximate time spent for set-up and printing was 12.50 minutes and 2 minutes, respectively. This study also calculated inventories for the computer monitors. The average computer monitors energy consumption for a typical 17-inch (431.8 mm) LCD monitor was 35 W, and the average computer energy consumption for a desktop computer was between 60 W and 250 W (Northwestern University, 2018). The study used the following formula [Equation [2]) to calculate the total energy consumption of the flatbed printer and the LCD monitor for 10 000 products:

$$Total\ Energy\ Consumption\ (KWh) = \frac{\text{Watts (W)}}{1\,000} \times \left(\frac{\text{Set−up Time (min)}}{60} + \frac{\text{Total Print Time (min)}}{60}\right) \times 10\,000 \quad [2]$$

2.2.4 Limitations and assumptions

The following limitations and assumptions could affect the results of this LCA.

- It was assumed that the electrical power required to the set-up process and the printing process were the same. Thus, the electrical power used for them were not separately calculated.
- The transportation between manufacturers and the printing facilities was excluded from the scope of this study.
- The secondary and tertiary packaging used to ship the consumables from their manufacturers to the printing facility are excluded from the scope of this study.

2.3. Life cycle impact assessment

The life cycle impact assessment used an endpoint-oriented life cycle impact assessment methodology called ReCIPe 2016 (Huijbregts, 2016). The ReCIPe model was selected for this study due to the use of a North American geographical scope. The model analyzes three endpoint impact categories: human health, ecosystems, and resources.

3. Results and discussion

3.1. Life cycle inventory results

In Table 1, we see the life cycle inventory for UV LED bottle inks. The material column lists the ingredients extracted from the SDS supplied by the ink manufacturer. However, many ink ingredients were unavailable on SimaPro v9.0. Hence, some materials were substituted based on secondary sources (Magdassi, 2009). Furthermore, the inventories as described in sections 2.1.1 and 2.1.2 were combined to form one overall inventory, whereas the second and third inventories consisted of the electrical consumption of the printing press and desktop devices, respectively.

Table 1: Life cycle inventory analysis of the UV LED bottle inks

Ink Component	Material	Material (Substituted)	LCI	LCI Type	Pedigree score
A[a]	Additives, unspecified	Additives	Pigment, paper production, unspecified, at plant/US-US-EI U	US LCI	(1,3,1,1,2,3)
O[b]	4-(1-oxo-2-propenyl)-morpholine	Bisphenol A	Bisphenol A epoxy-based vinyl ester resin, {GLO}| market for | APOS, S	US LCI	(1,3,1,1,2,3)
M[c]	2-phenoxyethyl acrylate	Ethoxylated (4) phenol acrylate	Ethoxylated alcohols, unspecified, at plant/US-US-EI U	US LCI	(1,3,1,1,2,3)
	Isobornyl acrylate	2-Ethylhexyl Acrylate	2-Ethylhexyl Acrylate/EU-27	Inventory Data 2.0	(1,3,1,1,2,3)
	(5-Ethyl-1-1,3-dioxan-5-)methyl acrylate	Methacrylic Acid	Methyl Methacrylate/ EU-27	Industry Data 2.0	(1,3,1,1,2,3)
	Tricyclo decane dimethyl diacrylate	Diethylene Glycol	Diethylene glycol, at plant/US- US-EI U	US LCI	(1,3,1,1,2,3)
PI[d]	Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide	Acetophenone	Acetophenone Airborne emission	SimaPro v9.0	(1,3,1,1,2,3)
	2-Phenoxyethanol	Benzophenone	Benzophenone Airborne emission	SimaPro v9.0	(1,3,1,1,2,3)
	Phenyl bis(2,4,6,-trimethylbenzoyl)-phosphine oxide		N/A		
PS[e]	4-Methoxyphenol	P-Nitrophenol	P-nitrophenol {GLO}| market for | APOS, S	Ecoinvent 3.0	(1,3,1,1,2,3)

[a]= additives, [b] = oligomers, [c] = monomers, [d] = photoinitators, [e] = phenolic sensor

In Table 2, we see the complete life cycle inventory analysis for the complete life cycle inventory analysis to produce 10 000 POP products.

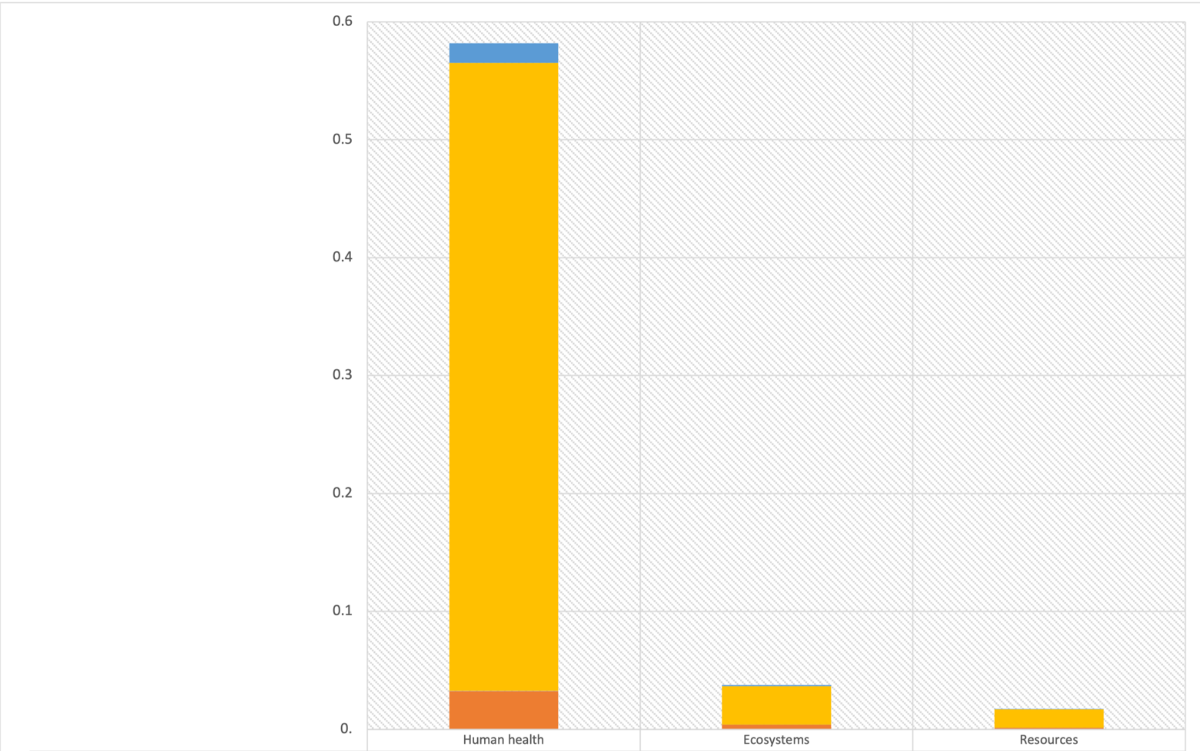
Table 2: Life cycle inventory analysis of the UV LED flatbed printing system for 10 000 products

Inventories	Components	Materials	Inventory name	Values/functional Unit	Inventory type	Pedigree Score
UV Bottle Inks[a]	UV Ink Bottle Magenta UV Ink Bottle Cyan UV Ink Bottle Yellow UV Ink Bottle Black		See Tables 2 - 5	2.36 kg	See Tables 2 - 5	
Electricity[b]	Printer	Electricity	Electricity, medium voltage, at grid/Ontario CA US-EI U	15,600 kWh	US-EI 2.2	(1,2,1,2,2,5)
	17" Dual LCD Monitors	Electricity	Electricity, low voltage, at grid/Ontario CA US-EI U	400 kWh	US-EI 2.2	(1,3,1,3,2,5)
Expendable Consumables[c]	Cleaning Liquid	Butyl diglycol acetate	Butyldiglycol acetate {GLO} butyldiglycol acetate production | APOS, S	10 g	Ecoinvent 3.0 allocation at point of substitution – system	(1,2,1,2,2,5)
	Lint-free Microfiber Cleaning Swabs	PP Process Polyester Process	Polypropylene, granulate, at plant/US- US-EI U Injection moulding, at plant/US- US-EI U Unsaturated polyester, resin, at plant/US- US-EI U Injection moulding, at plant/US- US-EI U	163.8 g	US-EI 2.2	(1,2,1,2,2,5)
	Painter's Tape	Kraft Paper Synthetic Rubber	Kraft paper, bleached, at plant/US US-EI U Synthetic rubber, at plant/US US-EI U	114.2 kg	US LCI US-EI 2.2	(1,3,1,2,2,3) (2,3,1,3,2,5)
	Expendable LDPE Bags	LDPE Process	Low density polyethylene granulate, at plant/US- US-EI U Extrusion, plastic film, at plant/US US-EI U	97.2 g	US LCI US-EI 2.2	(1,3,1,2,2,3) (2,3,1,3,2,5)
	Expendable Nitrile Gloves	Synthetic Rubber Process	Synthetic rubber, at plant/US- US-EI U Extrusion, plastic film, at plant/US US-EI U	53.4 g	US LCI US-EI 2.2	(1,3,1,2,2,3) (2,3,1,3,2,5)
	Paper	Recycled Pulp	Graphic paper, 100% recycled {RoW}| production | Conseq, U	219 kg	Ecoinvent 3.0 allocation at point of substitution – system	(1,3,1,3,2,5)

[a] = ultra-violet ink production and consumption, [b] = electricity consumption of printer and desktop, [c] = expendable consumables used for makeready and cleaning

3.2. Results of contribution analysis

Figure 1 shows normalized results of the contribution analysis of the UV flatbed printing.



	Human health	Ecosystems	Resources
Electricity, low voltage, at grid, Ontario/CA US-EI U	0.0164	0.0009	0.0004
Electricity, medium voltage, at grid, Ontario/CA US-EI U	0.5327	0.0326	0.0156
Ricoh UV Ink Bottle (CMYK)	0.0004	5.1E-05	2.54E-05
Paper	0.0322	0.0038	0.0012
Consumables	0.0001	1.32E-05	1.15E-05

Figure 1: Results of contribution analysis of the UV LED flatbed printing (normalized values)

The results indicates that the electricity consumption of the printing process had the greatest environmental impact in all three endpoint environmental impact categories including human health (91.6 % of the total impact), ecosystems (87.2 % of the total impact), and resources (90.1 % of the total impact). Specifically, diesel burned in the power plant contributed the most to human health and ecosystems, while natural gas burned in the power plant had the most contribution to resources.

Paper production generated the second largest environmental burden for all environmental impact categories (5~10 % of the total impact). In particular, the electricity used for the recycling process to manufacture recycled paper had the greatest contribution to human health. The natural gas consumed during the pulping process contributed most to ecosystems and resources.

The electricity consumption of the computer monitor had the third largest environmental impact for all environmental impact categories. It accounted for approximately 2 % of the total environmental burden for those impact categories.

The environmental impact of the ink was nearly negligible as it only accounted for 0.07 %, 0.14 %, and 0.15 % of the total environmental impact for human health, ecosystems, and resources, respectively. The consumables used for the printing process including cleaning liquid, lint-free microfibre cleaning swabs, LDPE bags, gloves, and painter's tape contributed the least to all environmental impact categories (less than 0.1).

The greatest environmental impact was generated by printer hardware similar to the findings of relevant literature that concluded inkjet printer systems were energy-intensive machinery. For example, Viluksela, Kariniemi, and Nors (2010) stated that digital printing methods consumed greater amounts of energy and ink consumption when compared to other methods. For the UV bottle inks and consumables inventories, it was expected that the environmental impact generated would be negligible in comparison to the electrical consumption of the print system. Similarly, the subsequent results indicated some impact on the degradation of human health, such as in the categories of human carcinogenics and non-carcinogenics, although the specific amounts were approximately 0.1.

4. Conclusions

The environmental contributions of the overall inkjet printing system largely stemmed from the electrical consumption of the printing press (medium voltage). Hence, the inkjet printing system was energy intensive. Despite the lack of LCA studies on the environmental impacts of UV LED inkjet presses, there is a general understanding that digital methods consume greater energy than traditional printing presses (Viluksela, Kariniemi, and Nors, 2010). However, the degree to which the energy consumption offsets the environmental contributions of other printing systems is underexplored. Future studies are recommended to compare multiple printing systems including UV inkjet printers to gain a thorough understanding of printing ink sustainability implications.

This study analyzed the environmental impact of a UV LED flatbed inkjet printing system with a focus on the materials and intermediate processes inventories based on a case study. First, the study found the electricity generated from the UV flatbed inkjet printer (medium voltage) contributed the most to all impact categories in comparison to all three material inventories. Second, the production of the polypropylene body of the lint-free microfiber cleaners contributed the most to the human health and ecosystem categories, whereas the production of recycled pulp contributed the most environmental impact to the resources category when analyzing the UV bottle ink and consumables inventory. Third, the study found that the ink ingredients did not contribute to the overall environmental impact in either of the three impact categories.

However, the UV LED ink inventories were difficult to assess due to the lack of available inventories. More research is needed to obtain a better and more reliable understanding of the UV LED inks. These include input and output figures like materials consumption, emissions, and waste output. The suitable functional units are the mass and the surface area of ink coverage, i.e., one square meter of ink coverage. This study also did not consider the environmental impact of transportation or disposal. Future studies are encouraged to examine the environmental impact of digital printing systems by optimizing electricity consumption processes. Likewise, the results of this study are only applicable to the production of the product under study. For this reason, it is encouraged to conduct similar studies of different print products.

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