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ORIGINAL PAPER

Environment-friendly and cost-effective solution for flexible packaging printing process by advancement in engraving process

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Abstract
Organic solvents have been commonly used in the printing process for a long time in gravure printing applications. Using organic solvents in solvent-based ink is responsible for fire hazards, volatile organic compounds emission, and increasing extra printing costs. The current study aimed to replace solvent-based ink with water-based ink to reduce volatile organic compound emissions and carbon footprints in gravure printing without affecting overall printing quality in order to fill a research gap because none of the studies were reported as best of all authors' knowledge. The polyethylene terephthalate film was printed by laser engraved cylinder having reduced engraving cell depth compared to electronically engraved printing cylinders which result in less consumption of printing ink, hence reducing the raw materials consumption. The cost of printing one kg of polyethylene terephthalate film with water-based ink was reduced by 1.85US$, and volatile organic compounds emissions were reduced from 3373 ppm to 2478 ppm compared to solvent-based ink. The use of water-based ink also reduced the carbon footprint by 3.04 kg. The current study shows that strict implementation of water-based ink has a high potential for saving the cost and reducing the emission of volatile organic compounds, which are very dangerous to the ambient environment, humans, and society. This study's outcome will help prepare the benchmark for green manufacturing systems in gravure printing applications to improve the environment and humanity.

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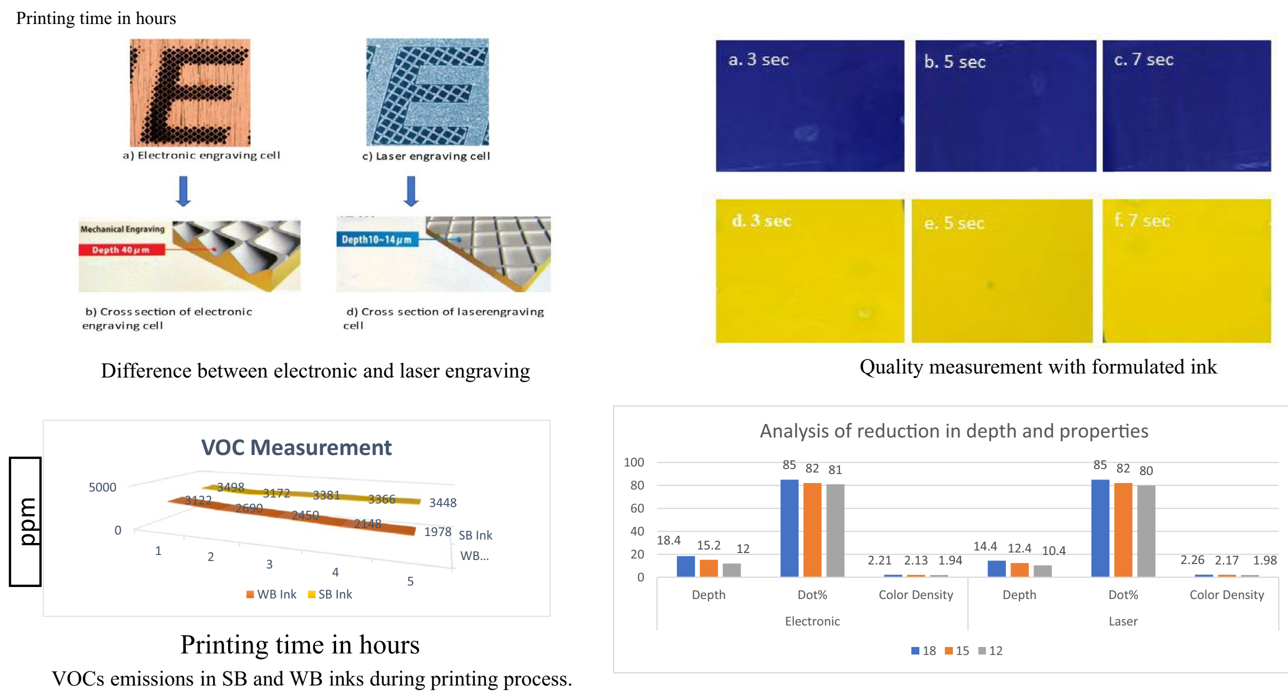
Graphical abstract



Keywords Gravure printing · VOCs emissions · Carbon footprints · Green manufacturing

Abbreviations

MNC	Multinational Companies
CPCB	Central Pollution Control Board
LE	Laser Engraving
GSM	Grams Square Meter
RPM	Rotation Per Minute
IPA	Isopropyl Alcohol
NGT	National Green Tribunal, India
EME	Electro-mechanical Engraving
AGPL	Afflatus Gravures Private Limited

Introduction

The global packaging industry is growing at about 6–7% per year and pretends to increase in future also. It is assumed that 80% of packaging is consumed by 20% of the population. Printing is one of the critical processes to enhance the aesthetic values of packaging. It provides the necessary information to the consumers, thus playing a pivotal role in transferring the information to the consumers. The directive defines printing as any reproduction activity of text and images in which ink is transferred onto paper or polymer surface using an image carrier. Inks on printing substrate dried through evaporation in a hot air hood duct before reaching to next printing station (Rong et al. 2004; Saeidpourazar et al. 2012) and leaving behind the dried layer of ink.

In India, most companies use SB inks for rotogravure printing due to good printability, machinability, excellent drying, and having no issues like foaming, pH control, adhesion, etc. (Epa 2001). Printing inks contain pigment, resin, functional additives, and vehicles. Vehicle plays a vital role in printing to transfer the ink compositions on the printing substrate (Howe et al. 2013). SB inks and solvents used for printing are highly volatile at room temperature. Solvent maintains the fluidity and ink transfer from engraving cell to substrate and must leave the printing substrates early as possible. SB inks for rotogravure printing generally have a solvent content of about 40–70% by volume, and a significant volume of solvent is evaporated in the environment. Consumption of solvent in rotogravure printing can be reduced by using WB ink, reducing ambient VOCs emission and carbon footprint. The advantages and disadvantages of SB and WB ink are shown in Fig. 1.

Although global environmental problems are typically considered part of national and international decision-making policies, there is still no futuristic approach adopted by the industries and governments for reducing or eliminating the use of solvent in flexible packaging printing processes (Aydemir and Özsoy 2021). Most printing units are trying to reduce the VOC emissions and CFPs from their printing

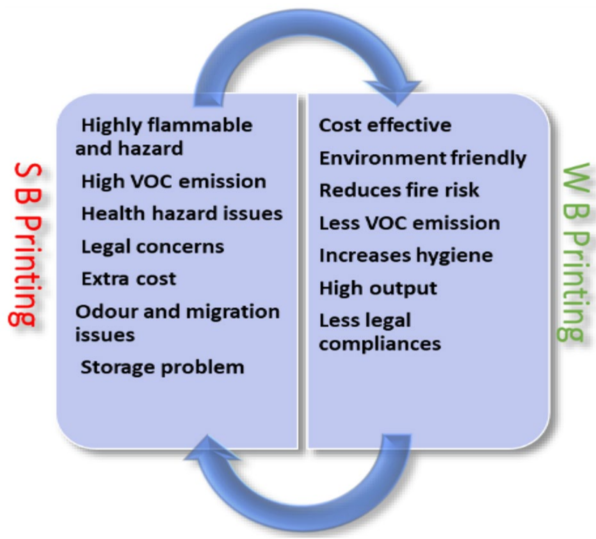


Fig. 1 Basic advantages and disadvantages of SB over WB ink

process by recovering solvent, reusing solvent, etc. (Kliopova-Galickaja and Kliaugaite 2018; Hansuebsai et al. 2020). The most significant sources of VOC emission in the printing process are identified in ink holding tub, transferred ink volume on printing substrate, and solvent used in shop floor area for cleaning activities. VOC emissions evaporating to surroundings contain approximately 98 to 99% of toxic compounds released by the printing industries (Kliopova-Galickaja and Kliaugaite 2018). In India, pollution control government bodies like NGT and CPCB impose restrictions on using solvents and SB inks for printing and packaging purposes. SB ink is lesser in Europe and the USA due to the adoption of printing through the flexographic printing method, but in India, the rotogravure printing process is prevalent; the Prime Minister of India also promised to cut India's total projected carbon emission by 1 billion tonnes by 2030 at the COP26 summit in Glasgow in November 2021 along with reduce the carbon intensity of the nation's economy by less than 45% by the end of the decade and net-zero carbon emissions by 2070.

To bridge this gap, efforts have been made to develop advanced water-based ink technology to reduce VOC emissions during the printing process (Ramirez and Tumolva 2018). Several studies have been performed on lowering or eliminating VOC emissions during flexible packaging printing. However, no collective studies have been reported yet, demonstrating the proper solution and benefits of replacing SB inks with WB inks (Ma et al. 2021; Mo et al. 2021) in the rotogravure printing process. The major bottlenecks for using water-based ink were to reduce the high volume of ink transferred to the substrate, which restricts the performance of drying and adhesion during the printing process. To overcome this problem, phase-wise changes were planned decisively, starting from modifying the engraving parameters by laser and developing water-based ink (Pugh and Guthrie 2002).

Keeping this in view, in the present study EME and LE cylinders were compared for suitability for WB ink by reducing the depth of engraving cell of EME and improving the cell geometry of LE. Cost analysis was also calculated with the consumption of solvents and inks to compare the pros and cons of research work (Novák et al. 2021; Cheryl Riley et al. 2021). This development helped in reducing the volume of transferred ink on the printing substrate without compromising the quality parameters (Charipar et al. 2018). Water-based ink was formulated and synthesized for the rotogravure printing process (Pi et al. 2016). The findings reveal that the developed ink was suitable for solvent-free printing and can replace SB ink, and has the potential to reduce VOC, CFP, and cost. The increase in pollution in India is alarming to adopt the sustainable approach for reducing the source of VOCs emission from the industries. Our current research outcomes show that WB inks are the most suitable alternative to minimize the environmental concerns in problematic areas and reduce the air quality index in many parts of India, which is a grave concern in India during the winter season especially.

Materials and method

SB ink was purchased from Sakata Inks, Noida, and solvents (ethyl acetate, acetone, and methyl ethyl ketone) from Jubilant Organosys, Noida, by AGPL. Water-based ink was synthesized as per the method (Sharma et al. 2021). The AGPL provided gravure printing cylinders for printing purposes. Printing substrate (PET film) thickness of 10 µm was purchased from the Film Division, Uflex Ltd, Noida.

Reduction in ink volume

Printing is the most critical process in packaging, and the cylinder has a significant role in flexible packaging printing (Epa 2001). Figure 2 shows the difference between electronic and laser engraving depth difference by a cross section of both. Electronic cells have a higher depth than laser cells (Fig. 2). Depth of cylinder was the significant apprehension for SB ink due to transferring a high ink volume by printing cylinder. With the reduced depth and geometry of engraving cells, printing quality parameters were compared, and the ink volume was optimized.

Difference in GSM

GSM was measured for SB and WB inks by coating PET film with electronic and laser cylinders using JM Heaford

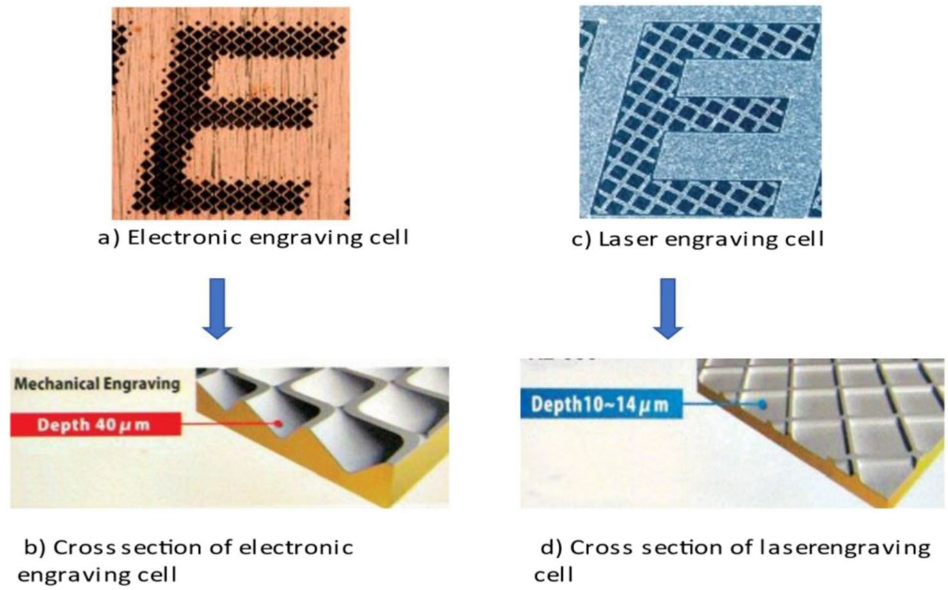


Fig. 2 Difference between the electronic (**a**, **b**) and laser (**c**, **d**) cell geometry from AGPL showing the cell depth difference which is the crucial factor for reducing the ink volume on the printing substrate

proofing machine, UK, by cyan and yellow printing inks. The sample was cut into 100 mm × 100 mm sizes and evaluated for GSM using an electronic balance (Shimadzu Corporation, Japan). Equations (1–4) were used to calculate dry and liquid inks' consumption for printing on PET film thickness of 10 µm.

$$\text{GSM} = \text{Thickness} (\mu\text{m}) \times \text{Density} \tag{1}$$

$$\text{Mass} = \text{Volume} \times \text{Density} \tag{2}$$

$$\text{Film length (m)} = \text{Film weight} \times 10\text{M}/(\text{film size} \times \text{GSM}) \tag{3}$$

$$\text{Dry consumption of ink} = \text{Film length} \times \text{film width} \times \text{ink GSM}/10\text{M} \tag{4}$$

The quantity of liquid ink will be calculated by multiplying the dry ink value by four. GSM of ink sample provides the primary assessment for the ink consumed or can calculate the ink requirement for better inventory management.

The difference in ink thickness

SB and WB inks were transferred on a substrate by proofing machines, morphological studies were measured by FE-SEM (Mira 3Tescan), and cross sections were prepared to determine the thickness layer of transferred ink on a substrate. The printed PET films were cut into small pieces, placed on the sample holder, and sputter-coated with Au–Pd before FE-SEM image observation (Pugh and Guthrie 2002).

Comparison of printing properties of SB and WB inks

The SB and WB inks were compared for composition (resin, pigment, additives, and vehicle), printing, and output quality parameters to study the performance of ink and its effect on cell depth (Ramirez and Tumolva 2018; Sharma et al. 2021). WB ink was synthesized with acrylic monomer, acrylic acid (AA), methyl methacrylate (MMA) and butyl acrylate (BA), 2-hydroxyethyl methacrylate (HEMA), 2-hydroxypropyl acrylate (HPA), and azobisisobutyronitrile (AIBN) was used as an initiator at 78 °C for 4 h. The inks were compared for viscosity, pH, and particle size, while printing properties were studied for color strength, adhesion, and drying.

Water solubility and viscosity

Water solubility and viscosity of both inks were measured to control the ink's flow property, which helped maintain the shade and color density according to standard shade cards. The viscosity of SB and WB inks was determined to observe its effect on printing quality and maintain the homogeneity of ink used for printing (Havlínová et al. 1999; Liu et al. 2019). To check the solubility of acrylic resin in water, 10 g of resin was added to 5–25 ml of deionized water with a gap of 5 ml, and the resulting mixture was stirred for 30 min at room temperature. The solubility of the resin in water was examined based on the transparency of the resulting solution mixture. The resultant solution's viscosity was determined with the help of NDJ-85 digital viscometer (Komal Scientific Co., India). Briefly, the viscometer's probe was dipped into the 25 ml aqueous resin solution, rotating at 250 rpm for one min at room temperature. The viscosity of the ink is the primary concern for maintaining the color values and shade variation of printing quality. Consistency in ink viscosity provided easy operation and less downtime of the printing press, providing more productivity and higher quality (Sharma et al. 2022).

Solid content

Ink deposition on printing substrate was measured by solid contents transferred by printing cylinder through transferred ink. The solid content of the ink helps to understand the ink's film forming and adhesion properties. To determine the percentage of solid contents in SB and WB inks, one gram of acrylic resin was poured into a petri dish and dried to a constant weight at 105 °C. The solid content (%) was determined using the following equation (Wang et al. 2011):

$$\text{Solid contents } (\%) = \frac{W_1}{W_2} \times 100 \tag{5}$$

where w_1 is the weight of resin after drying and w_2 is the weight of resin before drying.

pH

pH played a key role in WB ink for solubility of the acrylic-based resin in water and smooth transfer of ink constituents. pH also helped in dispersing the pigment in ink composition and uniform pigment distribution throughout the printing process. pH was tested by pH meter (ESICO, Model 1615, India) by dipping the probe in WB resin. Ammonia (35%) solution was used to maintain the pH of prepared ink at the targeted level.

The particle size of inks

Ink particle size was important for dispersion on the printing substrate. The smaller the particle size, the better the ink dispersion by tiny cells engraved on a cylinder (Pal and Fleming 2006). The average particle size of the inks was determined by Dynamic Light Scattering (DLS, Brookhaven Instrument) at a fixed scattering angle of 90°. The small number of inks (20 µl) was dissolved in 10 ml of deionized water and measured at 25°C in a triplet (Pal and Fleming 2006; Wołosiak-Hnat et al. 2019).

Color strength

Different colors printed on package provide the aesthetic values to package. Color strength was measured to study the effect on printing after reducing the cell depth by using SB and WB inks. WB ink had a higher pigment concentration compared to SB ink. LAB values were measured at five different places of a substrate (Lichtenberger; Wołosiak-Hnat et al. 2019; Hansuebsai et al. 2020) by SpectroEye, Spectrophotometer (Gretag Macbeth, Switzerland) (Suhag et al. 2022).

Adhesion

Adhesion of ink on printing substrate was studied to observe the bonding of ink on PET film. Pigment particles were dispersed in a mixture of resin, additives, and vehicles (Martínez-Landeros et al. 2019). The ink was applied on film by a proofer machine (RK Printing Proofer, UK) by coating a rod of 4 µm thickness at 250 rpm. Adhesion of printing ink on PET films was measured as per the method given by Aydemir et al. (Martínez-Landeros et al. 2019; Aydemir et al. 2021). Adhesion of ink on substrate is also responsible for rub resistance because of the stronger the adhesion, higher the rub resistance.

Drying rate

In rotogravure printing process, different colors are printed on PET film in a row, so drying of WB ink within the targeted time is a very critical factor for quality printing. The drying rate of ink is not crucial for SB ink due to the highly volatile nature of solvents, while it is most important for WB ink. Drying of print on PET film was measured immediately after printing as per the method (Liu et al. 2019).

Assessment of consumption of inks and solvents and financial analysis

The most printing press has 8–10 printing stations to print a single artwork by rotogravure printing machine. The cost reduction studies were conducted by mitigating the number of inks and solvents due to technological development in the engraving and printing process. Two cylinders of size 520 × 1100 mm were prepared, and electronic and laser-assisted engravings did a regular coating of 175 LPI. The coating was done by printing the EME and LE cylinder by white ink on PET film as per the method given by Sharma et al. The difference in dry weight was measured for both types of printed samples, and accordingly, liquid weight was also calculated. Cost reduction is only the key factor allowing the user to adopt or reject the developed technologies. Financial analysis was performed for WB and SB inks using laser cylinders to understand the adoption feasibility of study outcomes.

Measurement of VOC emissions

A comparative analysis of VOC reduction was performed to assess the decreased quantity of inks and solvent in printing process by EME and LE engraved cylinder (Jiao et al. 2020). A required amount of solvent and ink were mixed to maintain the running viscosity of ink on the printing machine. The difference in consumption of inks and solvent was calculated based on the quantity of ink consumed and solid contents transferred on the printed substrate. VOCs emissions were measured using a Gas Master VOCs meter (Swan Scientific LLP, New Delhi). The VOCs emissions (ton/year) were calculated by using Eq. (6):

$$X_{\text{VOC}} = M \times K \times 10^2 \tag{6}$$

where M is the volume of chemicals (solvents, paints, printing inks; ton/year) and K is the percentage composition of volatile substances (according to the material safety data sheet of the company).

Measurement of carbon footprint (CFP)

CFPs were estimated according to guidelines for estimating and measuring volatile organic compound emissions No. ECE/EB.AIR/WG.5/2016/4 (UN ESC 2016). The method for evaluating CO_2 was taken from the "Energy" guidelines of the Intergovernmental Panel on Climate Change (IPCC) Protocol for national greenhouse gas inventories (Volume 2 of the IPPC 1996). CFPs were calculated for reduce ink quantity, solvent consumption and solvent recovery during the proofing trial of gravure printing.

Case study for flexible packaging product

Flexible packaging products are available mainly in pouch form, and these pouches are generally manufactured according to the weight packaged in them. An additional study was conducted on actual packaging to understand the per pouch VOC and CFP emission. Different packages of wheat flour atta packets of 10 kg, 5 kg, 1 kg, and 500 gm were purchased from the local market to study the VOC and CFP emission. The total area of pouches was measured, and data were compared with the conclusion of the above study.

Results and discussion

Properties of SB and WB inks

The resin was the main constituent of ink and held all ink constituents. The resin had binding and film-forming

Table 1 A comparison of SB and WB ink properties indicates WB ink's advantages to suitability the printing requirements, and potential for replacement of SB ink

Parameters	Unit	SB ink	WB ink
GSM	g/m^2	2.14 ± 0.16	1.52 ± 0.12
pH		N/A	8.8 ±
Dry solid content	%	22 ± 0.08	40 ± 0.13
Pigmentation	%	15 ± 2	20 ± 2
Particle Size	µm	> 0.5	< 0.5
Dilution of ink	Solvent ratio %	60–70	IPA/DM ratio (20/80)
Ink thickness	µm	3.78 ± 0.17	2.72 ± 0.11

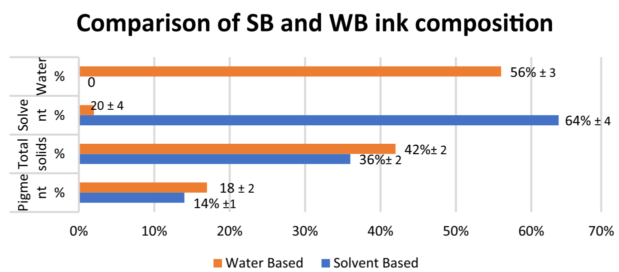


Fig. 3 Difference between SB and WB ink composition shows WB inks' advantages over SB ink

properties on the substrate, which is highly dependent on the thermal and mechanical properties of the resin. In water-based inks, acrylic monomers were used to prepare the waterborne resin. Pigmentation is a costly and critical part of printing inks and plays a crucial role in achieving color and shade properties. Pigment concentration varies in SB and WB ink (Table 1 and Fig. 3). The role of solvent in the printing process was to transfer all the composition of ink to the printed substrate by engraved cells and finally must evaporate from the surface of the film immediately. The organic solvent in SB ink was the main factor (about 60–70%) for odor problems in printed materials. In water-based ink, odor problems could be eliminated, and VOC emissions and odor problems could be controlled more effectively.

SB and WB inks GSM was 2.14 and 1.52 g/m^2, respectively. The pH of WB inks was 8.7 ± 0.2, which was required to maintain the resin's solubility and pigment dispersion in inks. The viscosity of SB and WB inks was 0.7 and 0.8 poise, respectively. These values follow ISO standards.

Dry solid contents were the quantity of printing substrate left after drying. The dry solid contents in WB ink (22%) were less compared to WB ink (40%) due to higher pigment concentration (10–15%). Pigment particle size was important for transferring the ink from tiny cells of the printing cylinder to the substrate. The laser-engraved cylinder transferred the ink quickly compared to the EME cylinder. It was also observed that particle size of WB inks was 556 and 452 µm for cyan and yellow inks, respectively, compared to particle size for SB ink (876 µm) for cyan ink.

Effect of engraving cell depth on printing

Electronic engraving depth was helical and higher. Using WB instead of organic solvent-based ink for flexible packaging was required to reduce the transferred volume of ink from printing cylinder to substrate. To achieve this goal, various studies were conducted with electronic engraved cylinders by optimizing the cell depth, LPI, cell size, and different types of styles. Unfortunately, none of the studies was able to provide hassle-free printing with WB ink. A comparison of the following parameters was performed at LPI-175, screen-100%, and the trial was conducted with white ink for cell depths of 18,15 and 12 µm, respectively.

An increase in cell depth of engraving cell increased the dot percentage and color density due to the higher volume of dry ink on the printing substrate (Fig. 4).

Reduction in transferred ink volume

GSM

GSM of printing was directly related to the cost and quantity of laminate. GSM of printed samples by electronic engraving was 2.08 g/m^2, and for laser, it was 1.52 g/m^2. The difference in GSM of electronic and laser engraving showed a difference of 0.56 g/m^2 of ink deposition related to the printing ink cost, color, and shade matching.

Ink thickness

Figure 5 shows the cross-sectional FE-SEM images of ink thickness for both the samples, and it was evident that the ink thickness of electronic engraving was higher than the laser-printed samples (Nielsen et al. 2015; Sharma et al. 2021). For electronically engraved printing, it was measured at 3.26 ± 0.64 µm, while for laser, it was measured 2.68 ± 0.51 µm. The total 0.58 µm thickness of WB ink was reduced in comparison with SB printed ink. The difference in ink thickness was due to a variation in GSM of printed samples (Aghajani Derazkola and Simchi 2020; Guo et al. 2021).

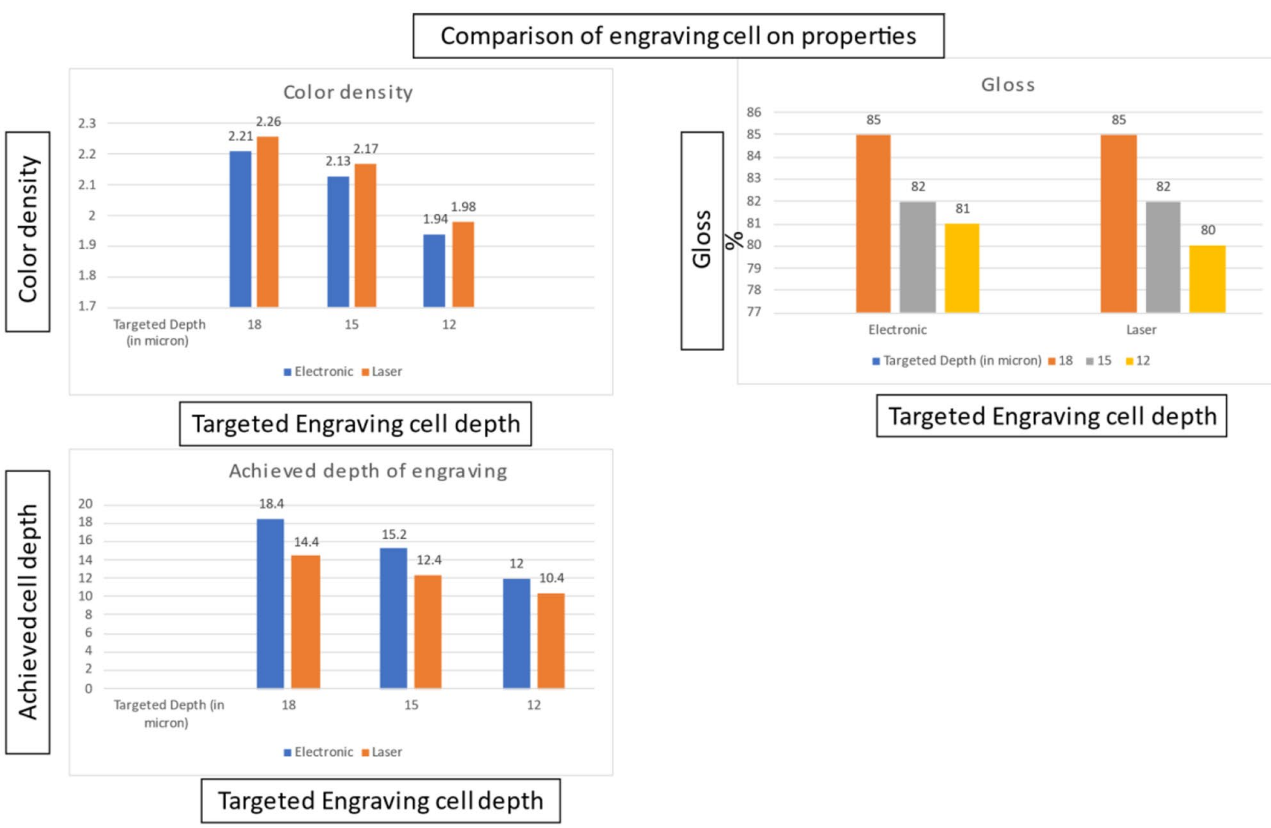


Fig. 4 Comparison of engraving depth and effect on printing properties. SD for depth, dot%, and color density for electronic and laser was measured sequentially with a tolerance of ± 0.19, ± 1, and ± 0.07

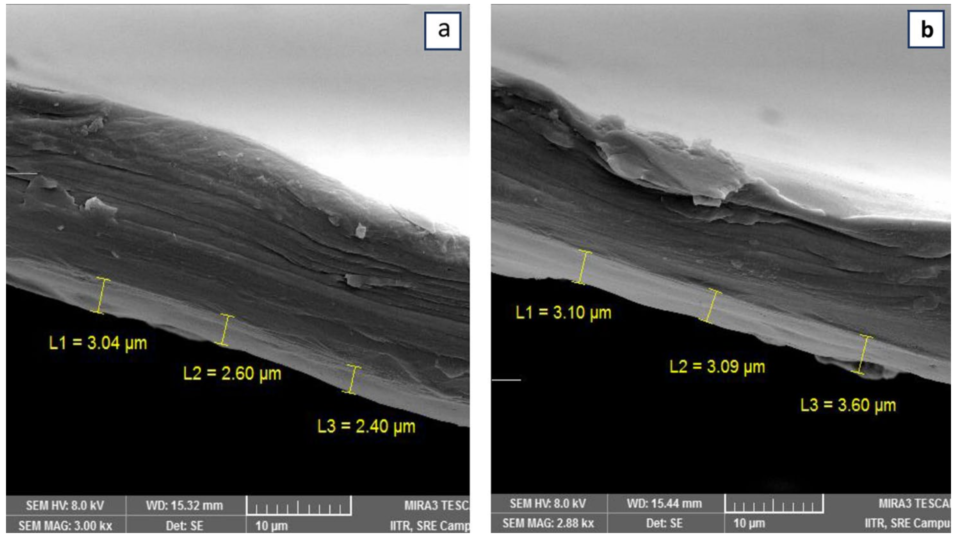


Fig. 5 FE-SEM images showing the thickness of **a** SB and **b** WB printed ink on PET film show that WB inks are lesser thicker than WB ink, thus confirming the reduced consumption on WB ink

Comparison of printing properties

Color strength

Color strength was measured for the high density (optical density = 1.5 as per ISO standard) color of magenta ink. Sample coated by laser cell was found to have more smooth and consistent printing than sample prepared by electronic cell. For sample-1, optical density was obtained at 1.39 and for laser engraving, it was 1.35. Therefore, laser engraving could replace solvent-based ink in rotogravure printing due to less cell depth and less volume of transferred ink.

Adhesion

Adhesion is the vital property of printing ink for forming a layer on the printing substrate and physical bonding. Adhesion of printing ink on PET films showed good bonding of ink composition with PET film. Tape test by 3 M adhesive tape (1.5 cm width) of printing samples showed more than 85% bonding for samples printed with SW and WB inks. The higher adhesion value improved the ink's rub and abrasion properties (Aydemir et al. 2021).

Drying rate

Drying is the primary concern for using the WB ink for the flexible packaging printing process because it reduces the volume of transferred ink. Therefore, it was possible to replace the SB with WB ink during the printing process (Rong et al. 2004). It was also observed that ink GSM could be reduced by maintaining the same printing quality parameters. In Fig. 6, cyan and yellow color represented the samples printed with SB and WB inks, respectively. There was no thumb impression in samples printed with cyan color (SB ink) after 5 s, whereas in the case of samples printed with yellow color (WB ink), a thumb impression was observed after 7 s. The drying time for substrate printed with WB ink would reduce on the printing machine due to hood temp when printed film passed through to the next printing station.

Reduction in consumption and cost-saving of inks

The PET film was printed with WB ink by electronic and laser engraved printing processes. Dry and liquid ink consumption during the laser engraved printing process was reduced by 27.4% and 28%, respectively, compared to the electronic engraved printing process (Table 2). The reduction in ink consumption was due to less cell depth of laser engraved cylinder compared to the electronic engraved cylinder, and it resulted in the transfer of less volume of ink on the printing substrate.

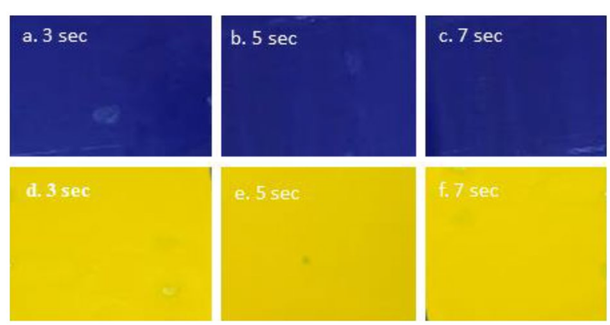


Fig. 6 The substrate's drying properties printed by cyan ink and image captured after **a** (3 s), **b** (5 s), **c** (7 s) by SB ink and **d** (3 s), **e** (5 s), **f** (7 s) by WB yellow ink confirm similar drying properties

Table 2 Less consumption of WB ink while printing the one kg of PET film in comparison to SB, which also shows the cost benefits of WB ink

Substrate	Thickness, μm	GSM	Film weight, kg	Dry ink consumption, kg	Liquid ink consumption, kg
Printing by electronic engraved cylinder					
PET film	10 ± 0.55	1.68 ± 0.03	1	0.124 ± 0.011	0.50 ± 0.09
Printing by laser engraved cylinder					
PET film	10 ± 0.55	1.68 ± 0.02	1	0.090 ± 0.008	0.36 ± 0.06
	Difference			0.034 ± 0.004	0.14 ± 0.02

PET film thickness 10 μm and film weight one kg

Consumption of solvents

The role of solvent in printing ink was like a vehicle that helped to transfer all the ink composition on the printing substrate, and finally, the solvent was evaporated from the film surface to the ambient environment. Solvents were also used to dilute the printing ink and clean machinery parts, equipment, and machine area. Most of the printing presses also have a solvent recovery plant to recover evaporated solvent during printing.

A reduction in the quantity of solvent was calculated from a reduction in ink (50–60%) consumption. A 1:1 ratio is maintained for ink dilution to achieve the standard viscosity. It means that 1 kg of SW ink requires one liter of solvent for the printing press. For WB ink, only 20% of IPA was mixed with 80% de-mineralized water to dilute the ink and achieve the targeted viscosity. Solid content for SB and WB ink was measured 22% and 40%, respectively.

Financial analysis

Consumption of inks (SB and WB) and solvents for printing 1 kg of PET films were calculated to study the cost difference for both printing processes. The reduction in the quantity of ink for laser engraved printing was found 11.48% compared to electronic engraving (Table 3). The difference in ink consumption was mainly based on the dry ink weight measured for both the engraving systems. About 80% reduction in cost was primarily due to less organic solvent consumption in WB inks. It was observed that 500 gm of ink, and 290 ml of organic solvent could be saved to print one kg PET film. The total saving was about US $ 1.85 when PET film was printed on a laser engraved cylinder for printing 1 kg of PET films using inks. This cost reduction indicates that WB inks have high potential to reduce the operation cost of the printing process and are also worthful for the commercialization of developed ink.

When the price is the primary concern to maintain the profitability of any organization in a pandemic situation, most industries are looking forward to reducing the operating cost. Lesser the operating cost provided the industries to compete in the market without compromising quality and profit. This research provides awareness to the packaging and printing industries to opt for the WB ink as a futuristic and economically viable solution, as discussed in Table 3.

Reduction in VOCs emission

WB ink contained solvents like ethyl acetate, acetone, IPA etc., which were used to maintain the viscosity and color. The VOC emissions in SB ink were between 3172 and 3498 ± 27 ppm with an average of 3373 ppm (Fig. 7). WB ink contained 10–20% of isopropyl alcohol to reduce the surface tension of water. The VOC emissions in WB ink were between 1978 and 3122 ± 18 ppm with an average of 2478 ppm. The WB ink reduced VOC emissions and maintained a less hazardous workplace with good workforce health.

Table 3 Reduction in consumption and cost benefits in $ of solvents and inks by using WB inks

		Ink (Cost in Kg)	Solvent (Cost in Kg)	Ink saving ($)	Solvent saving ($)	Total saving ($)
Reduction in quantity of ink and solvent (Kg)						
Ink	0.500 ± 0.041	11.76	1.05	5.88 ± 0.07	0.55 ± 0.03	6.40 ± 0.16
Solvent	0.290 ± 0.026	14.37	1.31	4.17 ± 0.04	0.38 ± 0.03	4.55 ± 0.08
					Saved amount	1.85 ± 0.10

*Dollar rate conversion was calculated as of 7May 2022 and the expected inflation rate is 4.3% in 2022

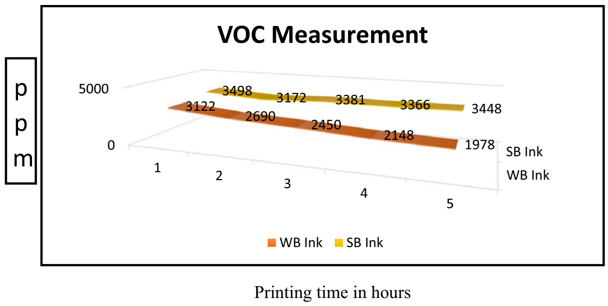


Fig. 7 Higher VOCs emissions by SB compared to WB inks during the printing process show the confirmation of research work for the reduction of VOC in the gravure printing process

Reduction in carbon footprints

CFPs could be reduced by using WB ink and reducing organic solvents in the printing process. The reduction in CFPs was calculated from the total reduction in ink and solvent and the recovery of evaporated solvent. The total decrease in CFPs using WB ink was 3.04 kg CO_2 equivalent per unit compared to SW ink for flexible packaging printing (Table 4).

Greenhouse gases and VOCs emissions caused global warming, and it was a significant challenge to provide a breathable atmosphere to the next generation. Several countries took many steps to control VOC emissions, but fewer efforts were contributed to this (Loyarte-López et al. 2020).

Case study for VOC and CFP for one pouch

Table 5 shows the industrial or commercial feasibility of the research findings discussed in this paper compared to actual commercial products. We compared our findings with existing products in the market. The data are tabulated in Table 5 to explain the VOC emission and CFP for printing one kg of PET film.

Table 5 shows that 10 kg of flexible packaging pouch emitted 9.23 ppm and 31 gm of CFP in the environment. The value of emission is reduced by reducing the packed product weight. This study is significant to understanding what is just throwing packaging waste after use and how much VOC and CFP were loaded into the environment. To reduce this issue in future, it is required to develop single-family polymer or decrease the volume of inks by lowering the color in the artwork of the package. Futuristic and focused research on scanning QR codes to get all the information in digital form, electronic packaging, and AI can reduce the printing requirement, hence being the better alternatives.

Table 4 Confirmation of the CFP emission reduction by WB ink compared to SB and WB inks, which confirms the research outcome as a reduction in carbon emission

Parameters	Quantity consumed	Unit	Factor	Emission factor (kg CO_2equivalent per unit)	Ref. nos
SB ink					
Ink	0.500 ± 0.023	kg	2.5	1.25 ± 0.08	Wang et al. (2011)
Solvent-acetone	0.5 ± 0.03	kg	2.19	1.095 ± 0.05	Wołosiak-Hnat et al. (2019)
Solvent top-up	0.5 ± 0.03	kg	2.19	1.095 ± 0.05	Wołosiak-Hnat et al. (2019)
Solvent recovery	1.25 ± 0.06	kg/kWh	0.81	1.04 ± 0.03	Epa (2001)
Total				4.48 ± 0.12	
WB ink					
Ink	0.36 ± 0.027	kg	2.5	0.900 ± 0.035	Wang et al. (2011)
Solvent-IPA	0.29 ± 0.018	kg	1.85	0.537 ± 0.022	Wołosiak-Hnat et al. (2019)
Total				1.437 ± 0.035	
Reduction in carbon footprints				3.04 ± 0.03	

Table 5 VOC emission and CFP calculation for different weight pouches printed by rotogravure printing process on polyethylene terephthalate film, which can be reduced by adopting the WB ink

Packaged flour weight (kg)	Size (mm)	Area of one pouch (m)	Area of 1 kg PET film (m)	Total VOC (ppm)	Total CFP (gm)
10	560*820	0.614	59.5	9.23	30.99
5	450*670	0.493	59.5	7.42	24.90
1	270*420	0.592	59.5	8.90	14.74
0.5	240*350	0.531	59.5	7.91	26.56

Limitation of the research work

This study still had uncertain factors due to the related parameters and measurements limitation. Proofing was performed at room temperature, and 50% RH and a new stylus were used for the engraving to avoid any physical difference in depth in engraved cells by electronic engraving. Emission factor uncertainties VOCs emission was measured on a proofing machine, and there were three proofing machines in a single room providing a standard entry covered with PVC strips. The accuracy of work can be affected due to ambient VOC concentration.

All calibration certificates of monitoring and measuring devices and masterpieces of calibration tools were evidenced by authorized certification agencies. These preventive measures were taken to control any effect on monitoring results to a certain degree to reduce the uncertainty factor for the research work.

Conclusion

The water-based ink was replaced with solvent-based ink using laser engraved printing cylinders without affecting color strength, adhesion, and drying rate. Water-based ink also showed a reduction in cost, volatile organic compounds emissions, and carbon footprint over solvent-based inks. This study also clinched that volatile organic compounds emissions and carbon footprint were significantly reduced and proven to be a sustainable and environment-friendly solution globally for rotogravure industries. The main goal is to anticipate the industries or authorities to cover the research gap and encourage them to adopt the new technologies. The findings also showed that laser engraved cylinders could replace solvent-based ink for gravure printing of flexible packaging. This study also enhances the awareness of consumers to demand more sustainable products. The outcome of this study can also be used to set the benchmark for industries to reduce volatile organic compounds and carbon footprint emissions according to regulations by government bodies.

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Declarations

Conflict of interest The authors have no competing interests to declare relevant to this article's content.

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