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CORRELATION OF INK PENETRATION WITHIN THE PRINTING SUBSTRATE AND PRINT-THROUGH EFFECTS IN OFFSET, GRAVURE AND SCREEN SUSTAINABLE PRINTS

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Abstract: *The drying process of printing ink on absorbent substrates in conventional printing techniques essentially takes place in two steps: the penetration of the ink within the printing substrate and the oxidation or oxy-polymerization process. The process of ink penetration within the printing substrate itself begins immediately after the ink is transferred using the impression cylinder, while the oxidation or oxy-polymerization process lasts up to several hours. In this research, the correlation between the value of ink penetration within the printing substrate and the print-through effect on prints produced using three different printing techniques was observed. In this analysis prints made on sustainable printing substrates were produced with a 30% share of non-wood cellulose pulp were observed in order to reduce the consumption of wood raw materials worldwide. The results of the research prove that the degree of ink penetration within the printing substrate correlates with the print-through effect in all analysed black prints (printed with one ink layer), while no correlation was found in the prints that were printed with three ink layers (cyan, magenta and yellow). That is the print-through effect is very low compared to the values obtained for ink penetration within the printing substrate. It was also found that the lowest values for ink penetration inside the printing substrate was achieved with offset printing process, and thus the lowest values for the print-through effect. Sustainable printing substrates achieve very low deviations compared to reference substrates made only from recycled wood pulp, which confirms the possibility of using these substrates for both secondary packaging and publications.*

Key words: gravure printing, ink penetration, offset printing, print-through effect, screen printing, sustainable printing substrates

1. INTRODUCTION

Today, commercial printing techniques are still on the market for the mass production of printed products that serve the multiple purposes of labelling, marketing, advertising, brand promotion and the dissemination of regulated information. The most common printing technique is offset printing, followed by flexographic printing, screen printing and gravure printing, whereby only the conventional printing techniques are considered (KBV Research, 2022).

Each printing technique is suitable for a specific graphic product. The choice of printing technique depends on the substrate, the printing ink and the intended use of the product. They differ in the way the ink is transferred from the inking unit to the printing substrate and in the way the printing form itself holds the ink. In the case of offset inks, the drying process can be described in the steps of penetration and oxidation/polymerization. In the first stage, the printed ink film penetrates between the fibres of the substrate, whereby the thickness of the ink layer must not be greater than the absorbency of the printing substrate. In this phase, the rapid setting/phase separation takes place, and the type of resin plays an important role once the ink has hardened and stopped transferring to other sheets within the print run. The final drying takes place via the mechanism of oxidation or polymerization of the ink. Oxidation, in which oxygen initiates the polymerization of free radicals from unsaturated oils, completes the drying of the ink on the printing substrate (Leach, 2008).

Gravure printing is a very old printing technique with low-viscosity inks that offers high quality reproduction on printing substrates, which is achieved by rapid drying of the ink. With conventional gravure inks, the drying process itself takes place through ink absorption and evaporation of the solvent (water or toluene). Inks with a dynamic viscosity of 0.05 to 0.2 Pa·s are used, compared to conventional offset printing inks, which contain a dynamic viscosity of 40 to 100 Pa·s (Kipphan, 2001; Leach, 2008). The possible applications are diverse and range from high-circulation magazines, catalogues and advertising brochures to the production of film packaging for food, snacks, sweets and medicines to decorative paper for laminate flooring and furniture.

There are around 1,200 gravure printing presses in Europe, which print over 1.2 million gravure cylinders

every year. By far the largest number of gravure printing machines is in Germany, with a total of 119 machines (Silver, 2021).
The screen printing technique is the most versatile method of ink transfer. This printing technique is used to transfer ink on many different substrates such as paper, textiles, ceramics, plastic, glass, wood and metal. When printing on absorbent printing substrates, the ink dries by absorption and evaporation of solvents, as in the gravure printing process, and the dynamic viscosity of the ink depends on the printing substrate, so it can range from 1.5 to 2.0 Pa·s (Leach, 2008).
With all three conventional printing techniques, it is possible to use water-based inks, which are more environmentally friendly. The gravure printing process also uses heavy metals such as copper, nickel and chromium. These metals are toxic and contaminate the environment if improperly disposed in contact with soil and water. The production process requires high energy consumption, particularly for drying the inks and running the machines, which increases carbon dioxide emissions that contribute to global warming. The amount of waste from engraving the cylinders has also increased, resulting in metal shavings that should be disposed of properly (Gravure Education Foundation, 2003). Today, more and more manufacturers are setting themselves new goals and challenges due to legal regulations and their own sustainability on the market. The most common goals are: carbon-neutral production; 100% recyclable, compostable or reusable products; a greater proportion of raw materials based on non-wood fibres or recycled wood fibres in printing material or from certified sources; 100% of energy from renewable energy sources; and more than 90% of non-hazardous waste which can be recycled or composted (Wessendorf, 2021). Due to the war in Ukraine and restrictions on the import of paper and cardboard from Russia, Europe is currently struggling with paper shortages (Fast Markets, 2022). Unfortunately, the usage rate of recycled paper varies greatly, as the final use changes depending on the desired quality of the original raw material. The use of recycled paper in Europe is highest in the printed packaging sector with 63.7%, for publications only 26.0% (18.6% for newsprint and 7.4% for other graphic products), and for household and sanitary products 6.9%, while other types of paper account for 3.4% (Blanco et al., 2013).
Since crop straw is treated as waste every year after harvest and large quantities remain in the fields, crop straw is becoming a potential source of fibre due to its global availability. Based on previous research, it was found that the addition of straw pulp from wheat or barley or triticale up to 30% of the content within the recycled fibre pulp creates a printing substrate with which various printing technologies achieve high quality printing (Plazonic et al., 2016; Bates et al., 2020; Plazonić et al., 2022; Bates et al., 2022; Cassel et al., 2023; Rudolf et al., 2023; Bates et al., 2024). In this study, samples printed according to the ISO 12647 standard using three printing techniques on printing substrates obtained with a 30% share of wheat or barley or triticale were analysed (International Organisation for Standardisation, 2013). The aim of this research was to observe the degree of ink penetration into the printing substrate in correlation with the print-through effect in black prints (printed with one layer of black) and in prints printed with three inks (printed with one cyan, one magenta and one yellow layer, which should achieve black coloration according to the theory of subtractive colour mixing) (Field, 1999).

2. MATERIALS AND METHODS

The experimental part of this research was performed in the following steps: 1. production of laboratory paper substrates; 2. printing of paper substrates; 3. ink penetration depth analysis; 4. analysis of print-through effect; 5. analysis of spectrophotometric values of prints.

2.1 Production of laboratory paper substrates

Straw of wheat (*Triticum spp*.), barley (*Hordeum vulgare L.*), and triticale (*Triticale sp*.), the most abundant crops in Croatia, was collected after harvest and manually cut into 3 cm long pieces with scissors. The cleaned straw was processed into semichemical pulp using the soda-pulp method.
The composition of laboratory-produced papers with a weight of about 42.5 g/m^2 was 30% unbleached wheat, barley or triticale pulp and 70% recycled wood pulp (Plazonić, 2016). They were formed using a Rapid-Köthen sheet former (FRANK-PTI) according to the standard EN ISO 5269-2:2004 (International Organisation for Standardisation, 2004).
The reference printing substrate (R) was made at the same laboratory procedure from 100% recycled wood pulp. Table 1 shows the abbreviations and composition of all paper substrates included in this research. The control paper (K), which is commercial paper made from 100% recycled wood pulp, was used to confirm the similarity of the properties of commercial paper with produced laboratory papers.

Table 1: Composition and marks of paper substrates

Paper substrate	Composition (%)	
K	0% straw pulp	100% recycled wood pulp
R	0% straw pulp	100% recycled wood pulp
30W70R	30% wheat straw pulp	70% recycled wood pulp
30B70R	30% barley straw pulp	70% recycled wood pulp
30T70R	30% triticale straw pulp	70% recycled wood pulp

2.2 Printing of paper substrates

Three main printing techniques commonly utilized for printing on absorbent substrates were used in this research. Offset printing is the predominant printing technique for publications and packaging, gravure printing is used for printing luxury products, publications and packaging in very long runs, while screen printing is used for products with special effects.

For all printing techniques, the printing substrates were printed in full tone with one layer of black and in full tone with three layers (cyan, magenta, yellow) according to the standard conditions of ISO 12647. As the printing sequence of the printing inks depends on the properties of the surface of the printing substrate and the rheological and transparent properties of the printing ink, sequential printing of inks was chosen in accordance with the standards, which means that the printing sequence for offset printing is cyan+magenta+yellow, for gravure printing is yellow+magenta+cyan and for screen printing is yellow+cyan+magenta (International Organisation for Standardisation, 2013; International Organisation for Standardisation, 2014; International Organisation for Standardisation, 2015).

Offset printing was carried out with conventional black Express ink (manufactured by Sun Chemicals) using a Prüfbau multipurpose test machine at a temperature of 23°C and a relative humidity of 50%. All samples were printed at a speed of 0.5 m/s and a pressure of 600N.

Gravure printing was done with a KPP laboratory gravure printing system using a printing cylinder with a mechanical hardness (HS) of 65 per Shore and an engraved printing plate at an angle of 37° with a diamond needle at an angle of 130° with a screen of 100 lines/inch, i.e. 40 lines/cm. The prints were made with Sunprop black ink (manufactured by Sun Chemicals) at a speed of 20 m/min, a temperature of 23°C and a relative humidity of 52%.

Screen printing was carried out with Epta Hi-Gloss inks from KIIAN S.p.A. on a semi-automatic machine from Shenzhen Juisun using a wiper with a mechanical hardness of 75 Shore and a mesh size of 120lin/cm at a temperature of 23°C and a relative humidity of 50%. After printing, the prints were moderately dried in the tunnel of the NP-2413 (380V) device from HIX corporation with warm air at a temperature of 55°C.

2.3 Ink penetration depth analysis

The surface topography plays a decisive role in the adhesion and transfer of ink, especially on laboratory paper that is not additionally industrially calendered and has a rough surface structure. Several factors influence the penetration of the ink into the substrate, including the printing pressure, whether it is a single or multi-layer print, the properties of the ink, the substrate properties, and the environmental conditions during the printing process.

The penetration depth of the ink (*Hp*) was determined by surface analysis using a non-destructive method of reflectance values based on the Kubelka-Munk theory (Equation 1) (Pauler, 2012; Yang et al., 2005; Yang et al., 2011). The ink penetration depth was determined from an average reflectance value of 50 spectrophotometric measurements measured by a spectrophotometer eXact, X-Rite with a measurement geometry of 45°/0° (D65/10°) at 457 nm (brightness) according to the Tappi T452 standard.

$$Hp = \frac{ln\frac{(1-R_0 \times R\infty)(1-Rp \times R\infty)(1-Rq\ /R\infty)}{(1-R_0\ /R\infty)(1-Rp\ /R\infty)(1-Rq \times R\infty)}}{ln\frac{1-R_0 \times R\infty}{1-R_0\ /R\infty}} \times D \quad (1)$$

where R_∞ is the reflectance value of unprinted paper substrate over opaque pad of unprinted papers, R_o is the reflectance value of unprinted paper substrate over a standard black background, R_p is the reflectance value of printed paper substrate over opaque pad of unprinted papers, R_q is the reflectance value of the reverse side of printed paper substrate placed over opaque pad of unprinted papers and *D* is an average value of unprinted paper thickness.

2.4 Analysis of print-through effect

The print-through is a qualitative measure that describes the visibility of the ink on the reverse side of the printed paper substrate. This phenomenon occurs when the opacity of the paper substrate itself is reduced by the infiltration of the ink carrier after printing, the penetration of the ink pigments into the paper, and the inherent transparency of the paper. The print-through is precisely defined as the appearance of a thin layer of ink on a paper substrate that is visible through a white background (Eriksen et al., 2005; Eriksen et al., 2006).

The colour difference (ΔE^*_{00}) between the CIE colorimetric values L*, a* and b* on the reverse side of the printed paper substrate and the white background of the unprinted paper substrate was used to calculate the print-through effect. These colorimetric values were determined using a spectrophotometer (X-Rite Exact, D50/2°), and Equation (2) was used to calculate the colour difference, thereby revealing the print-through effect.

$$\Delta E^*_{00} = \left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_c S_c}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_C S_H} \quad (2)$$

where $\Delta L'$ represents the transformed lightness difference, $\Delta C'$ represents the transformed chroma difference, $\Delta H'$ represents the transformed hue difference, R_T is the rotation function; k_L, k_C, and k_H represent the factors for the variation in the experimental conditions; and S_L, S_C, and S_H are the weighting functions. The definition of tolerance colour difference (ΔE^*_{00}) is presented in Table 2 (Yang et al., 2012); (Kumar, 2003).

Table 2: Tolerances of colour difference

Euclidean difference value	Euclidean difference tolerance
< 0.2	Average human eye does not see the difference
0.2- 1	Average human eye sees negligible difference
1- 3	Very small difference – optimal ΔE^*_{00}=2
3- 6	Clearly visible
6- 12	Difference, extremely large
> 12	Great difference, unacceptable

2.5 Analysis of spectrophotometric values of prints

Spectrophotometry is the science that forms the basis for colour measurement. Colour perception is a connection between physics and physiology that was recognized very early on when the physicist Isaac Newton contributed to spectrophotometry and colorimetry in 1704 with his attempts to divide white light into spectral colours.

However, the colour perception of the human eye itself was defined by the physician Thomas Young in 1802. Young is considered to be the first to describe how colour is perceived in the eye with the help of the three receptors red, green and blue. Today we know that every colour experience can be fully described with three numerical values (L*, a*, b*) (Young, 1802; Heesen, 2015).

In this research, the colorimetric values of obtained samples with three different printing techniques were considered in the CIELAB colour space. CIELAB is a colour space that was defined in the 1976 by the International Commission on Lighting was created to represent colours more faithfully than the CIEXYZ colour space and enables the numerical definition of all colours visible to the human eye (Field, 1999).

3. RESULTS AND DISCUSSIONS

To observe the correlation between the ink penetration depth inside the ink into the paper substrate and the print-through effect, prints produced using three printing processes (offset printing (o), gravure printing (g), screen printing (s)) were analyzed. In this paper, samples printed with only one layer of black ink and samples printed with three layers of ink were compared, which create a dark brown colour that should theoretically be black (cyan+magenta+yellow). The colorimetric values of the single-layer and three-layers prints were additionally placed in the CIELAB colour space to observe the difference between the colours obtained on the prints with the three different printing techniques.

The correlation results between the ink penetration depth within the printing substrate and the print-through effect on prints obtained with three printing techniques are shown in Figure 1.

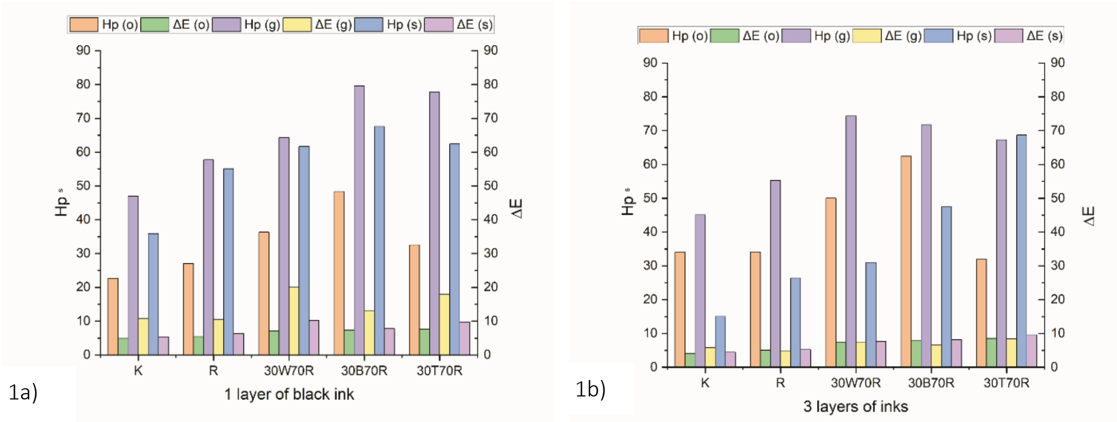

Figure 1: Correlation between the ink penetration depth within the printing substrate (Hp) and the print-through effect (ΔE^*_{00}) for prints obtained with the offset printing process (o), gravure printing process (g) and screen printing process (s) with: a) one layer of black ink and b) three layers of cyan, magenta and yellow ink

Figure 1a shows the correlation between the ink penetration depth and the print-through effect, where the highest ink penetration depth was achieved in the gravure printed samples on sample 30B70R and sample 30T70R, while the highest print-through effect was obtained with samples 30W70R and 30T70R using the gravure printing process.

Observing the printing techniques it is evident that the lowest values for ink penetration depth for all paper substrates were achieved with offset printing ($Hp_{(o)}$ = 22.71 - 48.33), while the highest values for ink penetration depth were achieved with gravure printing ($Hp_{(g)}$ = 47.05 - 79.56). These results are directly related to the dynamic viscosity of the ink. Inks with a high viscosity create a lower ink penetration depth, while inks with a low viscosity in relation to high fluidity result in a high ink penetration depth when used on the same paper substrates. From the results of the print-through effect, it can be seen that the values are greater than ΔE^*_{00} = 4.94, which is considered a clearly visible difference between the colours. This is to be expected as the table is used for the tolerance of colour differences when comparing very similar shades or prints, whereas in this analysis a comparison of the reverse side of the print and the unprinted paper substrate was used.

Figure 1b does not show the correlation between ink penetration depth and the print-through effect. The values of all samples for the print-through effect were very similar or equal, while the highest values for the ink penetration depth were calculated for samples 30W70R and 30B70R. The print-through effect is significantly lower for these samples than for prints with a single ink layer. For these prints, the print-through effect is a maximum of ΔE^*_{00} = 8.52, whereas it is a maximum of ΔE^*_{00} = 20.11 for prints with only one layer of black. It can therefore be concluded that these substrates are more suitable for multi-colour printing than for mono-colour printing with only black ink. The relationship between dynamic viscosity and ink penetration depth is also observed when printing three layers of ink, which are printed in different sequences to achieve a theoretical black colour or dark brown coloration. The highest values of ink penetration depth were achieved in the gravure printing process ($Hp_{(g)}$ = 44.05 - 74.34), while the lowest values were obtained when printing with the offset printing process ($Hp_{(o)}$ = 31.91 - 62.24).

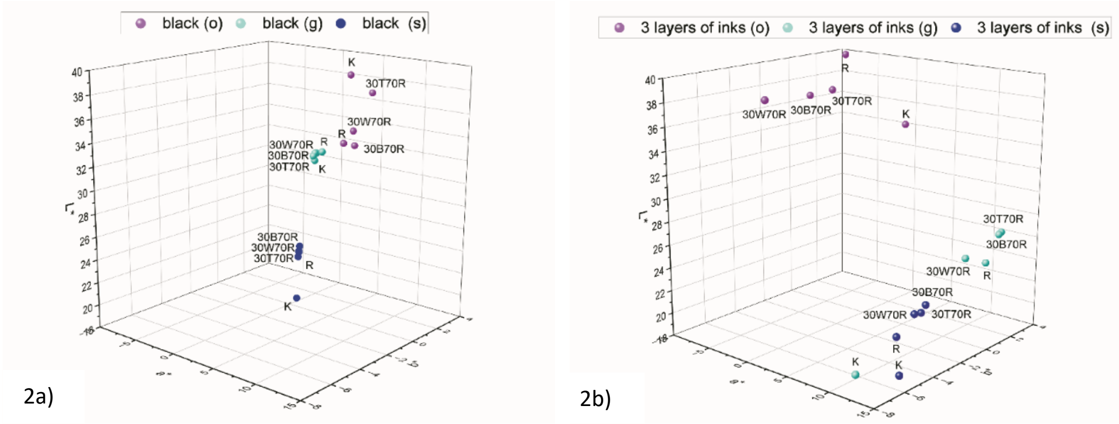

Figure 2: Colorimetric values of prints with single ink layer (black) (2a) and 3 layers of ink (brown)(2b) produced with the offset printing process (o), gravure printing process (g) and screen printing process (s)

By observing the colorimetric values of black prints with a single ink layer (2a) and three ink layers (2b), a strong scattering of colours can be observed in Figure 2b, while in Figure 2a very similar colours were printed with gravure and screen printing techniques, while a lower colour scattering is visible in offset prints. The largest colour differences between the prints depending on the printing technique used can be observed in the L* coordinate (Figure 2a). Figure 2b shows the largest differences between the placement in the CIELAB colour space of offset prints on the one side and gravure and screen prints on the other. Offset prints are located at much higher L* values (L* = 33.82- 39.56) than other prints (L* = 18.07- 25.87), which is most likely due to the sequence of ink printing, where the yellow ink is printed last in offset printing, while gravure and screen printing techniques are used as the first printing ink. Comparing the prints produced using gravure and screen printing techniques with three layers of ink, differences in the b* coordinate can be observed, most likely due to the last ink printed, i.e. cyan in gravure and magenta in screen printing.

4. CONCLUSIONS

The results of the research prove that the degree of ink penetration within the printing substrate correlates with the print-through effect in all analysed black prints (printed with one ink layer), while no correlation was found in the prints that were printed with three ink layers (cyan, magenta and yellow). Meaning the print-through effect is very low compared to the values obtained for ink penetration within the printing substrate. It was also found that the lowest values for ink penetration inside the printing substrate was achieved with offset printing process, and thus the lowest values for the print-through effect.
It has been confirmed that the dynamic viscosity of the ink is directly related to the penetration depth of the ink. It was proven that the analyzed paper substrates are more suitable for multi-colour printing than for mono-colour printing with only black ink if a lower print-through effect is to be achieved.
It is confirmed that the printing sequence of inks is a very important factor in achieving uniform coloration of prints produced with different printing techniques. Sustainable printing substrates with a 30% straw pulp content achieve very low deviations compared to reference substrates made only from recycled wood pulp, which confirms the possibility of using these paper substrates in all three printing processes.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Bates, I., Plazonić, I., Petric Maretić, K., Rudolf, M. & Radić Seleš, V. (2022) Assessment of the UV inkjet ink penetration into laboratory papers within triticale pulp and its influence on print quality. *Color Technology*. 138, 16–27. Available from: doi: 10.1111/cote.12563

Bates, I., Plazonić, I., Radić Seleš, V. & Barbarič-Mikočević, Ž. (2020) Determining the quality of paper substrates containing triticale pulp for printing industry. *Nordic Pulp & Paper Research Journal.* 35. 272–278. Available from: doi: 10.1515/npprj-2020-0009

Bates, I., Plazonić, I., Rudolf, M. & Bratić, D. (2023) Quantification of the influence of ink penetration and optical ink density on the print-through of printed straw-based papers. *Applied Science*. 14, 288. Available from: doi: 10.3390/app14010288

Blanco, A., Miranda, R. & Monte, M. C. (2013) Extending the limits of paper recycling: improvements along the paper value chain. *For. Syst.* 22 (3). 471-483. Available from: doi: 10.5424/fs/2013223-03677

Cassel, N., Chalancon, J., Pisaroni, H. Plazonić, I., Radić Seleš, V. & Bates, I. (2023) Utilization of Laboratory Papers with Non-Wood Fibres as Printing Substrates Observed Through the Maximum Ink Penetration Depth. *Tehnički glasnik*. 17 (1). 32-37. Available from: 10.31803/tg-20220213172821

Eriksen, O. & Gregersen, O. W. (2005) The influence of ink pigment penetration and paper structure on print through. *Nordic Pulp & Paper Research Journal.* 20 (2). 242-246. Available from: doi: 10.3183/npprj-2007-22-03-p364-370

Eriksen, O. & Gregersen, O. W. (2006) Ink pigment location measured as the position of clay in coldset ink. *Nordic Pulp & Paper Research Journal*. 21 (4). 460–465. Available from: doi: 10.3183/npprj-2006-21-04-p460-465

Fast Markets. (2022) *How Russia's invasion of Ukraine impacts the European pulp and paper industry.* Available from: https://www.fastmarkets.com/insights/how-russias-invasion-of-ukraineimpactsthe-european-pulp-and-paper-industry [Accessed 6th September 2024].

Field, G. G. (1999) *Color and Its Reproduction. 2nd ed*. Pittsburg, PA, USA, GATF Press.

Gravure Education Foundation and Gravure Association of America. (2003) *Gravure: Process and Technology*. Rochester, New York, (GAA) Gravure Association of America.

Heesen, R. (2015) *The Young-(Helmholtz)-Maxwell Theory of Color Vision*. Available from: https://philsci-archive.pitt.edu/11279/1/The_Young-%28Helmholtz%29-Maxwell_Theory_of_Color_Vision.pdf [Accessed 1st September 2024].

International Organisation for Standardisation. (2013) ISO 12647-2. Graphic technology — Process control for the production of halftone colour separations, proof and production prints — Part 2: Offset lithographic processes. Geneva, Switzerland, International Organisation for Standardisation.

International Organisation for Standardisation. (2014) ISO 12647-4. Graphic technology — Process control for the production of half-tone colour separations, proof and production prints — Part 4: Publication gravure printing. Geneva, Switzerland, International Organisation for Standardisation.

International Organisation for Standardisation. (2015) ISO 12647-5. Graphic technology — Process control for the manufacture of half-tone colour separations, proof and production prints — Part 5: Screen printing. Geneva, Switzerland, International Organisation for Standardisation.

International Organisation for Standardisation. (2004) ISO 5269-2. Pulps — Preparation of laboratory sheets for physical testing Part 2: Rapid-Köthen method. Geneva, Switzerland, International Organisation for Standardisation.

KBV Reseaarch Knowledge based value (2022) *Analysis of Market Size & Trends*. Available from: https://www.kbvresearch.com/commercial-printing-market/ [Accessed 1st September 2024].

Kipphan, H. (2001) *Handbook of Print Media*. Berlin, Heidelberg, Springer.

Kumar, M. (2003) *Interdisciplinarnost Barve 2. Del*. Maribor, Slovenia, Društvo koloristov Slovenije.

Leach, P. (2008) *The printing ink manual*. 5th ed. Dordrecht, Netherlands, Springer.

Pauler, N. (2012) *Paper Optics – optical and colour science related to the pulp and paper industry*. Kista, Sweden, AB Lorentzen & Wettre.

Plazonic, I., Bates, I. & Barbaric-Mikocevic, Z. (2016) The effect of straw fibers in printing papers on dot reproduction attributes, as realized by UV Inkjet technology. *BioResources*. 11 (2), 5033-5049. Available from: doi: 10.15376/biores.11.2.5033-5049

Plazonić, I., Bates, I. & Vukoje, M. (2022) Changes in Straw-Containing Laboratory Papers Caused by Accelerated Ageing. *Heritage*. 5 (3), 1836-1851. Available from: doi: 10.3390/heritage5030095

Rudolf, M., Plazonić, I., Petric Maretić, K. & Bates, I. (2023) Overall Stability Valorization of Printed Sustainable Packaging Paper Containing Triticale Straw Pulp. *Processes*. 11 (5), 1465. Available from: doi: 10.3390/pr11051465

Silver, J. (2021) *Gravure printing in Europe - status and trends*, Gravure Global Edition. Available from: https://era-eu.org/wp-content/uploads/JS_Gravure-Status-and-Trends_engl.pdf [Accessed 1st September 2024].

Wessendorf, A. (2021) Tightly integrated prepress and print production. *Verpackungs Druck & Converting*. Available from: https://www.flexotiefdruck.de/dossiers/tightly-integrated-prepress-and-print-production/ [Accessed 4th September 2024].

Yang, L., Fogden, A., Pauler, N., Sävborg Ö. & Kruse, B. (2005) A novel method for studying ink penetration of a print. *Nordic Pulp & Paper Research Journal*. 20 (4). 423. Available from: doi: 10.3183/npprj-2005-20-04-p423-429.

Yang, Y. G., Hu S. & Liu, F. (2011) Establishment of Ink Penetration Model and the Calculation of Penetration Depth inside Paper. *Advanced Materials Research*, 295-297. 2028-2032. Available from: doi: 10.4028/www.scientific.net/AMR.295-297.2028

Yang, Y., Ming, J. & Yu, N. (2012) Color Image Quality Assessment Based on CIEDE2000. *Advences in Multimedia.* 11, 11. Available from: doi: 10.1155/2012/273723

Young, T. (1802) On the Theory of Light and Colours. *Philosophical Transactions of the Royal Society of London.* 92. 12-48. Available from: doi: 10.1098/rstl.1802.0004