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Scientific article

Analysis of uneven ink coverage on more environmentally acceptable printing substrates

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***Abstract**: Due to the effects of fires and climate change, as well as illegal and unsustainable logging of forests and their conversion for other purposes, the world is facing a reduced amount of forested land. Trees are still the main source of cellulose fiber, so the paper industry is continuously focused on searching for new sources of raw material. Awareness of sustainable development and ecology requires the use of alternative sources of cellulose fibers to produce paper from agricultural crop residues that are rapidly renewable and cheap to produce. Cereals such as wheat, barley and triticale have been shown to have favourable properties suitable for cellulose fiber production. In this study, laboratory paper substrates were prepared from recycled wood fibers with the addition of alternative non-wood fibers in a mass fraction of 30%, and their reproduction quality was analyzed. The produced paper substrates were then printed using the gravure printing technique, which provides the highest reproduction quality in the field of packaging printing. The analysis of reproduction quality was performed based on the parameter of non-uniform ink coverage with conventional and UV inks on the obtained laboratory printing substrates with non-wood fibers. The values of uneven ink coverage of laboratory printing substrates were determined by image analysis in the program ImageJ and are presented graphically. It was found that all analyzed printing substrates printed with high-quality gravure printing technology achieve high ink coverage in the range of 97% to 98%.*

***Keywords**: gravure printing, environmentally acceptable printing substrates, non-wood fibers, uneven ink coverage, reproduction quality.*

1. Introduction

Since printing substrates are traditionally made from cellulose fibers derived from wood, deforestation has increased significantly, leading to global awareness of the consequences of deforestation and the importance of reusing waste paper as a source of recycled cellulose fibers. It is therefore not surprising that over the past decade the use of recycled paper in the paper and board industry has increased globally. Recycled paper currently accounts for about 50% of the total paper fiber production used worldwide [1]. However, paper production cannot be based solely on recycled fibers from waste paper, nor can they be effectively used for all types of paper, nor can they be used forever as a raw material. Cellulose fibers become shorter and of lower quality with each recycling process, sometimes allowing them to be recycled up to seven times [2]. Therefore, pulp from recycled fibers is usually enriched with a certain amount of virgin fibers to increase the strength and quality of the paper produced [3]. Alternative sources of fiber for the paper industry are being analyzed and implemented worldwide, and their use depends on the region where they can be collected. Today, only a very small percentage of graphic printing paper is made from non-wood fibers, which can be divided into agricultural residues, primary crops and naturally growing plants [4, 5]. Non-wood pulp accounts for about 10% of the worldwide pulp production for producing paper [6]. Cereals such as wheat, barley and triticale have been shown to produce a valuable material after harvest, straw, whose cellulose fibers exhibit favourable properties for paper production. Since they are obtained from the residues of agricultural crops that grow quickly and are cheap to produce, they represent a very interesting source of cellulose fibers for paper production [7-9]. As the properties and composition of the printing substrate are one of the most important factors that undoubtedly affect the overall quality of printing on packaging, this study was aimed at comparing laboratory-produced substrates made from pulp of recycled wood fibers and different types of non-wood fibers in a ratio of 7:3 with the substrate made only from recycled wood pulp to determine whether the addition of alternative non-wood fibers achieves the same or even higher print quality. The printing substrates are printed using the gravure printing technique, which provides the highest reproduction quality in the packaging printing sector. This printing technique is cost-effective due to its excellent durability in long runs and is now mainly used for printing luxury products and decorative printing, as it is the only seamless conventional printing process [10, 11]. Analysis of the reproduction quality was performed using the parameter of uneven ink coverage with conventional and UV inks on the obtained laboratory printing substrates with non-wood fibers and compared with prints on the laboratory printing substrate consisted only of recycled wood pulp (N). The values of uneven ink coverage of laboratory printing substrates were determined by image analysis in the program ImageJ and are presented graphically.

2. Experimental part

The experimental part of this study was performed in four steps: 1. obtaining pulp from straw; 2. producing laboratory paper substrates; 3. printing of laboratory paper substrates with gravure printing technique; 4. analysis of uneven ink coverage on laboratory paper substrates.

2.1. Obtaining pulp from straw

The residues of agricultural crops were collected after grain harvest in the continental part of Croatia. Cereal straw was converted into pulp, and the conditions of the wheat, barley and triticale straw pulping process are summarized in the study by Plazonić et al. (2016) [12].

2.2. Producing laboratory paper substrates

The laboratory-produced paper substrates with the addition of 30% wheat, barley or triticale pulp were prepared using a Rapid-Kothen sheet former (FRANK-PTI) according to the standard EN ISO 5269-2:2004 [13]. Papermaking process under laboratory conditions is presented in a study by Plazonić et al. (2016) [12, 14]. The reference sample was the laboratory paper made of recycled pulp only, marked with N, while the laboratory papers made of 30% straw pulp and 70% recycled pulp, marked with 3NW, 3NB and 3NTR, were the main focus of this study. The basic properties of the analyzed laboratory-made paper substrates are shown in Table 1.

Table 1 *Characteristics of paper substrates [12, 14-16]*

Paper substrates	Composition, $W_{non\text{-}wood\ pulp}:W_{wood\ recycled\ pulp}$ (%)	Thickness (μm) ISO 534 (2011)	Ash (%) ISO 2144 (2015)	Roughness, R_a (μm) ISO 4287–1 (1997)
N	*0:100*	*94.00 ± 2.79*	*4.73 ± 0.22*	*4.15 ± 0.34*
3NW	*30:70*	*101.50 ± 5.32*	*3.64 ± 0.07*	*4.25 ± 0.56*
3NB		*99.10 ± 4.06*	*3.32± 0.67*	*4.37 ± 0.34*
3NTR		*99.40 ± 6.20*	*3.99 ± 0.15*	*4.40 ± 0.39*

2.3. Printing laboratory paper substrates with gravure printing technique

The printing of laboratory paper substrates was carried out by simulating the gravure printing technique according to conditions summarized in Table 2. All laboratory paper substrates were printed in full tone with conventional and UV-curable inks at a temperature of 23 °C and a relative humidity of 52% [17].

Table 2 *Printing process conditions [17]*

Printing technique	Gravure
Machine	*KPP Gravure System laboratory device*
Printing cylinder	*mechanical hardness of 65 Shore (HS)*
Cell angle	*37°*
Screen	*100 lines/inch (40 lines/cm)*
Diamond angle	*130°*
Ink used	*conventional Sunprop, Sun Chemical*
	Solarflex UV, Sun Chemical

2.4. Analysis of uneven ink coverage on laboratory paper substrates

The analysis of reproduction quality on laboratory paper substrates was divided into two phases: the analysis of monocolor prints (conventional and UV) and the analysis of multicolor prints (conventional and UV). To obtain a monocolor print, one layer of cyan (C), magenta (M), yellow (Y), or black (K) conventional ink was applied to the observed laboratory paper substrates. Multicolor prints were obtained by applying two layers of ink: Yellow and Magenta (Y+M), Yellow and Cyan (Y+C), Cyan and Magenta (C+M) and three layers of ink: Yellow, Cyan, and Magenta (Y+C+M). The reproduction quality assessment was carried out by microscopic analysis of the prints with the Dino-Lite device, using the ImageJ image analysis program and plugin 3D Surface Plot.

3. Results and discussion

The reproduction quality assessment was done on prints produced by gravure printing with conventional inks (solvent-based) and UV-curable inks in full tone printing. The results of measuring uneven ink coverage on monocolor and multicolor prints obtained with conventional inks (c.i.) and UV-curable inks (uv i.) are presented graphically and numerically. Tables 2 and 3 show the topography of the samples using a 3D graphic representation of prints made with one ink layer (cyan, magenta, yellow, and black) of conventional and UV-curable inks.

***Table 2** 3D graphic representation of the uneven ink coverage results on monocolor samples (C, M, Y, K) printed with conventional inks*

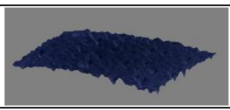
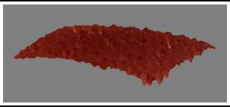
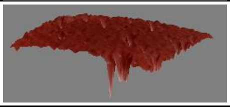
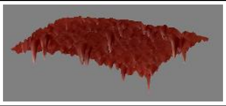
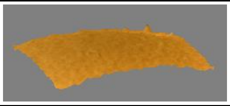
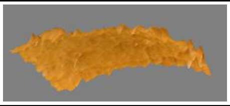
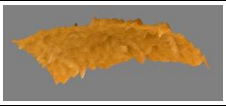
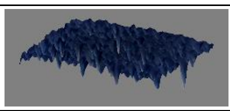
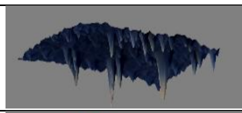
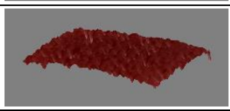
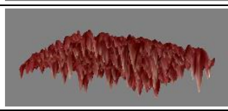
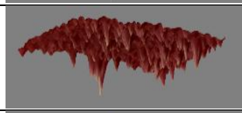
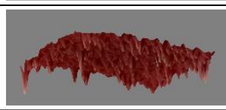
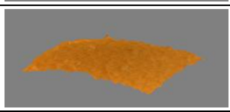
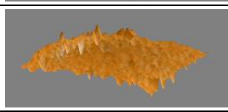
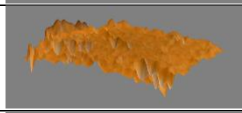
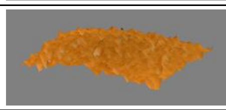
Paper substrates	***N***	***3NW***	***3NB***	***3NTR***
Cyan print				
Magenta print				
Yellow print				
Black print				

***Table 3** 3D graphic representation of the uneven ink coverage results on monocolor samples (C, M, Y, K) printed with UV-curable inks*

Paper substrates	***N***	***3NW***	***3NB***	***3NTR***
Cyan print				
Magenta print				
Yellow print				
Black print				

Viewing the 3D graphic representation of the monocolor gravure prints with conventional inks in Tables 2, it was found that the uneven ink coverage was reduced for cyan, magenta, and yellow prints produced on a printing substrate from recycled wood pulp (N), while a greater increase in uneven ink coverage was noticed for the printing substrates with the addition of non-wood pulp (3NW, 3NB, 3NTR). Black prints are perceived as equally well reproduced regardless of the type of substrate, i.e., with the same degree of uneven ink coverage on all printing substrate. In relation to the printing substrate used, monocolor gravure prints with UV-curable inks showed similar results of uneven ink coverage on the printing substrate as prints with conventional inks (Table 3). Also, in the case of prints with UV-curable gravure ink, the most uniform ink coverage was observed for the substrate without the addition of non-wood pulp (N). This trend of increasing ink coverage unevenness can be explained by a slight increase in the roughness of the printing substrate with the addition of non-wood pulp. From the results shown in Table 1, it can be seen that the R_a of printing substrates with the addition of non-wood pulp increased up to 6%. In general, it is evident that the UV-curable inks on the analyzed printing substrates did not achieve uniform ink coverage to the extent that conventional gravure printing inks did.

Figure 1 shows the measured values of uneven coverage of prints with one layer of ink (cyan, magenta, yellow and black) with conventional ink (marked with a solid line) and UV-curable ink (marked with a dashed line). From the results shown in Figure 1, it can be seen that the prints with cyan and magenta inks contain equal uneven ink coverage obtained with conventional ink and with UV-curable ink (from 97.62% to 97.72%), while greater deviations are visible in the prints obtained with yellow and black inks (from 97.66% to 97.98%), where higher values of non-uniform ink coverage were obtained with UV curable ink. (98.18%).

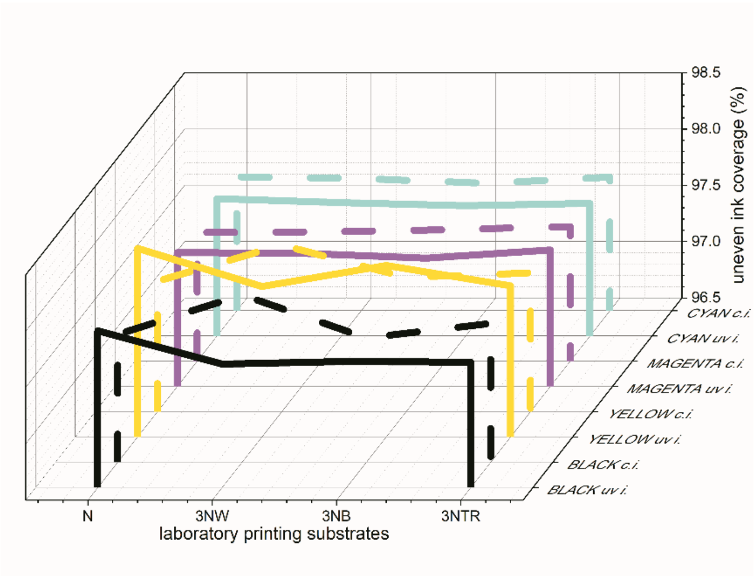


Figure 1 *Assessment of reproduction quality - numerical presentation of the results of uneven ink coverage of C, M, Y and K gravure prints obtained with conventional inks (c.i.) and UV-curable inks (uv i.)*

The 3D graphic representation of the printed multilayers (Y+M, Y+C, C+M and Y+C+M) of conventional and UV-curable inks are shown in Tables 4 and 5 to illustrate the topography of the samples, while Figure 2 presents the measured values of uneven coverage of prints with multi layers of ink (Y+M, Y+C, C+M and Y+C+M) with conventional inks (marked with a solid line) and UV-curable inks (marked with a dashed line).

Table 4 *3D graphic representation of the uneven ink coverage results on multicolor samples (R, G, B and brown) printed with conventional inks*

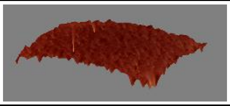
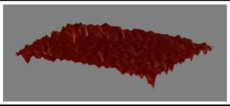
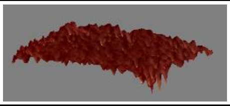
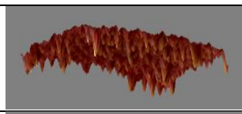
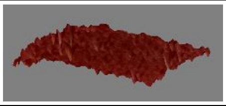
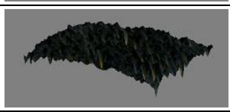
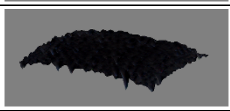
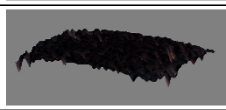
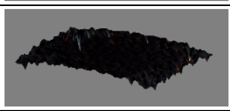
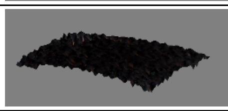
Paper substrates	***N***	***3NW***	***3NB***	***3NTR***
Y+M print				
Y+C print				
C+M print				
Y+C+M print				

Table 5 *3D graphic representation of the uneven ink coverage results on multicolor samples (R, G, B and brown) printed with UV-curable inks*

Paper substrates	**N**	**3NW**	**3NB**	**3NTR**
Y+M print				
Y+C print				
C+M print				
Y+C+M print				

The 3D representation of the prints showed that the uneven ink coverage of the multicolor print (Table 4 and 5) was higher than that of the monocolor print (Table 2 and 3). This behavior was observed for prints with conventional inks and UV-drying inks. When looking at the 3D appearance of prints made with conventional ink, greater changes in ink coverage are observed for prints made on printing substrates with non-wood fibers than for prints made on printing substrates with recycled wood fibers. The appearance of prints produced with UV-curable inks showed very similar results on all prints, regardless of the composition of the printing substrate. Prints with greater uneven ink coverage were prints made on 3NW and 3NB printing substrates with Y+M print ink, prints made on 3NW printing substrates with Y+C ink, and prints made on 3NB and 3NTR printing substrates with Y+C+M ink. For multicolor prints, the same level of uneven ink coverage was observed for all prints, regardless of whether they were produced with conventional or UV-curable ink.

Figure 2 shows the measured uneven ink coverage values of two-layers and three-layer ink (Y+M, Y+C, C+M, and Y+C+M) when printed with conventional ink (marked with a solid line) and UV-curable ink (marked with a dashed line).

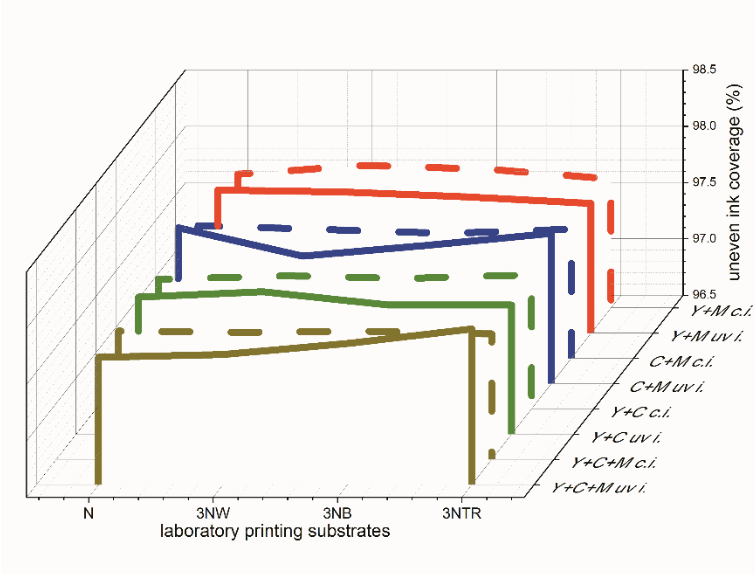


Figure 2 *Assessment of reproduction quality - numerical presentation of the results of uneven in coverage of gravure prints (Y+M; C+M; Y+C; Y+C+M) obtained with conventional inks (c.i.) and UV-curable inks (uv i.)*

The uneven ink coverage results from Figure 2 showed that all prints have very similar values (from 97,62% to 97.89%), while slightly higher values were obtained for all multicolor prints with UV-curable inks. Y+C prints and Y+M prints with UV-curable ink showed the highest non-uniform ink coverage, while the lowest was obtained for three-layer prints (Y+C+M) with conventional ink.

4. Conclusion

Due to the long-standing desire to conserve natural resources such as wood in order to reduce the proportion of wood consumed in the production of paper, that is, in the specific case printing substrates, this study analyzed the usability of printing substrates with the addition of non-wood fibers by comparing achieved quality of the prints on such printing substrates with ones on printing substrates made only from recycled wood pulp. Conventional printing inks and UV-curable gravure inks for one-layers, two-layers, and three-layers printing were used to analyze the achieved reproduction quality of monocolor and multicolor prints. It is found that gravure prints on all analyzed printing substrates contain very similar values of uneven ink coverage. The results showed a high ink coverage in the range of 97-98%, which means that environmentally acceptable printing substrates are printed with high quality. Based on the obtained results, it could be concluded that printing substrates with the addition of non-wood fibres are a good substitute for printing substrates made of wood fibers. It should also be noted that substrates with non-wood fibers are well suited for printing with conventional and UV-curable inks, both for monocolor and multicolor printing. From this research, it is also concluded that, in addition to the results of measuring the value of uneven coverage with ink, it is necessary to show images of the samples for a better understanding.

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