The Effect of Straw Fibers in Printing Papers on Dot Reproduction Attributes, as Realized by UV Inkjet Technology

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Paper performance qualities strongly depend on the origin of cellulose fibers. Awareness of environmental issues and sustainable development has led to the increase in the use of recycled printing papers. Recovered fibers are often used as a substitute for virgin wood fibers in the production of certain types of papers. As recovered fibers cannot provide the same quality level of paper products as virgin wood fibers, alternative sources of virgin cellulose fibers need to be identified. The aim of this research was to analyze the printability of laboratory papers made of different contents of straw pulp. Therefore, the printing papers were formed using straw pulp of three different cereal species (wheat, barley, and triticale) and mixing them with recycled newsprint in different weight ratios. The printability of these laboratory papers was analyzed by classifying dot reproduction quality based on four dot reproduction attributes. Printed dot reproduction greatly affects the quality of reproduction in graphic products, as dots are the most important element in multi-color reproduction of texts and images. It was confirmed that laboratory papers containing straw pulp provide the same or even better dot reproduction quality than laboratory control papers formed only of recycled newsprint.

Keywords: Straw pulp; Printing paper; Ink jet printing; Printing quality; Dot Reproduction attributes

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INTRODUCTION

Achieving good quality prints depends on a variety of print quality parameters. A number of quality parameters affecting the perception of quality reproduction have been classified by Pedersen. Dot and line quality, mottling, graininess and resistance of prints (rub, scratch, crinkle and chemical) are some of the important parameters used in the evaluation of quality reproduction (Pedersen *et al*. 2010). It is important to point out that these parameters are not necessarily independent; many of them are correlated with and strongly dependent on paper roughness, paper flatness, glossiness, and the used printing technique. As the printing paper undoubtedly has a strong effect on the quality of prints, this research was additionally focused on the printability of laboratory papers formed using straw pulp of three different cereal species (wheat, barley, and triticale) and mixing them with recycled newsprint in different weight ratios.

For the purpose of achieving optimal quality reproduction, it is necessary to raise the awareness in relation to printing paper qualities and possibilities offered by printing techniques. Wood is still the most widely used raw material for pulp in the global paper production. However, due to the use of raw materials in the supply of paper industry with cellulose fibers, along with the overexploitation of forests, new sources of virgin fibers have to be identified. Higher awareness of environmental issues and the issue of sustainability has resulted in the increased use of recycled fibers; consequently this has caused gradual growth in the demand for papers made of recycled fibers, which has not ceased to date. Recovered fibers are often used as a substitute for virgin wood fibers, mostly in the production of boards and specific types of papers. However, they cannot provide the same printing paper quality as virgin wood fibers (Minor and Atalla 1992; Nazhad 2005; Hubbe *et al*. 2007). Fibers isolated from annual agricultural crop residues present an interesting alternative raw material for pulp and paper industry because of their numerous advantages; they are economical, abundant, and renewable (Leponiemi 2008; Jahan *et al.* 2009; Sirdach 2010). On the other hand, there are still some disadvantages related to: fiber supply (sources of fibers are harvested over a short period and therefore large storages are required, they are bulkier than wood which increases transport and storage costs); production (higher content of silica than wood makes the conventional chemical recovery system inappropriate, while appropriate production technology is not available and it may become even more expensive than equipment used for wood); demand stage (the actual size of tree-free market is unknown) of using non-wood fibers for pulp and papermaking (Roberts 1996; Chandra 1998).

In European countries such as Italy, Germany, France, Spain, Greece, Hungary, and Croatia, production in agriculture is relatively high because of adequate climate and fertile soil (Youngquist *et al*. 1996; Spöttle *et al*. 2013). Therefore, the utilization of agricultural residues in the paper industry has potentially great importance, especially because they are still to a large extent burnt or ploughed back into the ground. Various field crop species could represent an alternative to using hardwoods in paper and graphic products (Kamoga *et al*. 2013).

The aim of this research was to examine the effect of straw pulp used in the preparation of laboratory papers, on the quality of reproduction in digitally printed dot patterns. Because of the decreased demand for printed media, digital printing techniques have become the most economic techniques for small runs. Therefore, it is to be assumed that digital printing techniques will progressively replace conventional newspaper printing techniques. Consequently, analyses were conducted on laboratory papers of different fiber composition in terms of their origin (different weight ratio of straw pulp and recycled newsprint) and printed with a UV ink jet printer. The quality assessment of prints included analysis of dot reproduction, based on analysis of dot area and dot shape descriptors (roundness, aspect ratio, and solidity).

EXPERIMENTAL

The experimental part of this research was divided into four stages: 1. obtaining straw pulp; 2. forming laboratory papers with different contents of straw pulp; 3. printing paper sheets; and 4. analyzing quality reproduction in all paper sheets.

Obtaining Straw Pulp

The agricultural residue of annual crops (wheat, barley, and triticale), which is available in continental Croatia was used in the process of obtaining pulp. After harvesting those winter crops, the straw was collected from the fields. All straw was cut manually into 1- to 3-cm-long pieces before it was converted into pulp according to the soda method (Plazonic *et al*. 2014a). Operating conditions of straw pulping are presented in Table 1.

Table 1. Operating Conditions of Straw Pulping

Agricultural residues	Pulping method	Extraction conditions
Wheat straw	Soda pulping	Temperature of 120 °C, alkali level of 16% for 60 min, and a 10:1 liquid to biomass ratio
Barley straw		
Triticale straw		

After the thermal treatment under controlled and defined extraction conditions, the pulp slurry was removed from the black process liquor by decantation and rinsed with water. In a Valley beater (Techlab Systems (TLS), Spain), pulp was diluted with tap water to maintain the pulp suspension at a 1.5% consistency and fiberized. Finally, the pulp was drained by Manual Sheet Former TAPPI (Techlab Systems (TLS), Spain) and allowed to dry to a moisture content of approximately 7% at the room temperature.

The pulp samples obtained were analyzed for kappa number, brightness, and ash content in accordance with the respective ISO standards (ISO 302 (2004); ISO 2470-2 (2008); ISO 2144 (2015)), the results of which are presented in Table 2.

Table 2. Properties of Pulp

Component	Wheat pulp	Barley pulp	Triticale pulp
Kappa number	30.0	29.6	32.4
Brightness D65, %	22.41 ± 0.55	27.16 ± 0.62	19.45 ± 0.41
Ash, %	6.57 ± 0.45	6.65 ± 0.29	7.28 ± 0.42

Forming Laboratory Papers with Different Contents of Straw Pulp

The obtained unbleached straw pulp was mixed with recycled newsprint in different weight ratios in order to form laboratory papers needed for this research. Commercial UPM News C paper was used as a basic component to which straw pulp had been added. Its characteristics are presented in Table 3.

Table 3. Properties of Commercial UPM News C paper

Basis Weight (ISO 536), gm^{-2}		42.5
Brightness D65 (ISO 2470-2), %		58.0
Roughness Bendtsen (ISO 8791-2), ml min^{-1}		100.0 - 160.0
R_a (ISO 4287-1), %	Machine direction (MD)	2.576 ± 0.319
	Cross machine direction (CD)	3.166 ± 0.254
Ash (ISO 2144), %		10.00 ± 0.04
CWSN		9A

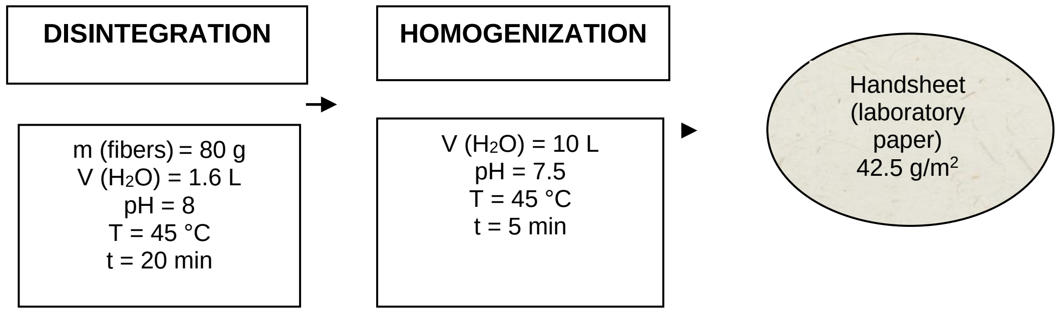


Fig. 1. Workflow of laboratory paper production

According to the general process flow of forming laboratory papers presented in Fig. 1, printing papers containing straw pulp and a control paper sample were formed (all presented in Table 4).

Table 4. Paper Composition

Laboratory paper	%		
	Newsprint	Straw pulp	
N	100	0	-
1NW	90	10	Wheat
2NW	80	20	
3NW	70	30	
1NB	90	10	Barley
2NB	80	20	
3NB	70	30	
1NTR	90	10	Triticale
2NTR	80	20	
3NTR	70	30	

Laboratory paper formed only of recycled newsprint was used as a control paper sample (denoted N) in the process of comparing the quality reproduction of papers containing straw pulp. It is important to point out that all printing papers were laboratory papers formed using a Rapid Köthen Sheet Machine (Frank–PTI GmbH, Birkenau, Germany), which resulted in different qualities for the wire side (bottom side) and felt side (top side).

Analysis on Unprinted Laboratory Papers

Most of laboratory paper properties were determined according to ISO standards, except for tensile strength and surface paper strength, which were determined by TAPPI standard.

The thickness of laboratory papers was determined according to ISO 534 (2011), which defines a single sheet thickness as a distance between one surface of a paper and the other, measured under an applied static load. These measurements were taken with a digital electronic thickness gauge (Enrico Toniolo S.R.L., Italy), where cylindrical stainless steel weight makes pressure of 0.5 kg/cm^2 (49.03 kPa).

Ash content in laboratory papers is defined in accordance with the ISO 2144 (2015) standard. Determination of residue (ash) on ignition at 900 °C is based on ten analyses performed on each paper sample.

By TAPPI standard method, TAPPI T494 (2001), the test piece of laboratory paper was stretched to the point where the rupture occurs. The maximum tensile force the test piece can withstand before it breaks and the corresponding elongation of the strip were measured and recorded.

The standard Dennison wax pick test was performed to determine the highest wax number that will not give paper failure when pulled from the surface in accordance with the TAPPI T459 (1993). This test uses a series of waxes having different adhesiveness that are numbered from 2A to 26A. The lowest wax number that does not disturb the test surface is quoted as the Critical Wax Strength Number (CWSN) and is used as a measure of the surface strength of uncoated and coated papers. A high CWSN designates a strong surface strength.

To study the behavior of water absorption of the laboratory papers made of different contents of straw pulp, water absorption tests were carried out according to the international standard ISO 5637 (1989). All the samples were first dried at 105±2 °C during 24 h in an oven. The dried paper samples were weighed (mass m_1) and were immersed in a water bath at 23 °C, during a time period of 5 minutes. At the end of the immersion period, the paper samples were removed from the distilled water and drained by gravity for 2 minutes before wet weight values had been determined (mass m_2). Water absorption percent was calculated using the Eq. 1,

$$M_t(\%) = \frac{m_2 - m_1}{m_1} \times 100 \qquad (1)$$

where M_t is the water absorption percent after time t, m_1 is the oven-dry weight of the paper sample, and m_2 is the paper sample weight after water immersion.

The roughness of a paper surface is a very important physical paper property to consider for achieving optimal quality reproduction of graphic products. The roughness of the felt side of all printing papers, which were later printed for the purposes of further analysis, was determined using a Surface roughness tester TR200 (Innovatest Europe BV, Maastricht, The Netherlands). Measurements were provided by the stylus method, vertical to the paper surface. Surface roughness measurements were based on a few roughness parameters, with the most commonly used being arithmetic mean surface roughness (R_a). This is defined as the arithmetical mean of the sums of all profile values (Fig. 2). Arithmetic mean surface roughness is calculated according to Eq. 2 (ISO 4287-1 (1997)):

$$R_a = \frac{1}{L}\int_0^1 |Z(x)|\, dx \qquad (2)$$

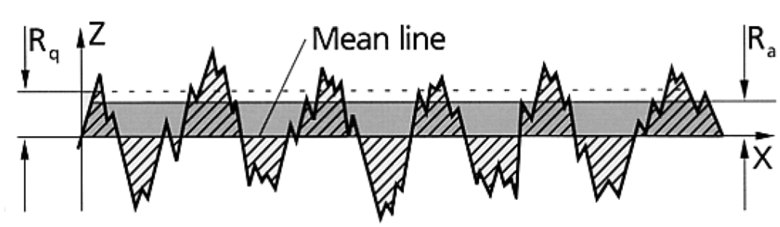


Fig. 2. Plot of roughness profile

The quantity R_a is one of the most effective surface roughness measures because it gives a good general description of the height variations in the surface. The root mean square roughness (R_q) is more sensitive to occasional highs and lows and is defined as the geometric average height of roughness-component irregularities from the mean line measured within the sampling length, *L*. Figure 2 presents a plot of a profile where the R_a and R_q levels are shown to present the differences between them. '*L*' is the total length scanned on the horizontal axis, and '*x*' is a reference mean line over which the topographical heights were measured. Z_x is the height amplitude at each iteration over the full measurement length from x=0 to L-1. The surface profile height '*Z*' is calculated with reference to the mean line and plotted on the vertical axis (Alam *et al*. 2012).

Printing Laboratory Papers

The printability of all laboratory papers was examined after printing them using an AGFA, Anapurna M1600 (Agfa Graphics NV, Düsseldorf, Germany), UV-curable ink jet printer. The ink jet printings process is a relatively new printing process that is well-suited for a variety of printing applications. The ink jet process is known as a computer to print technology, whereby the ink is transferred directly to the printing paper by means of a jet system. In comparison with traditionally used printing processes (offset, flexography, *etc*.), this type of printing process requires minimum production space and can be mounted on the production line and used on many different substrates. In this technology, a finite amount of liquid (ink or dye) is transferred directly onto a printing substrate. Therefore, an image carrier, such as printing plate, is not needed in the process (Lundberg *et al*. 2009). The thickness of the ink layer in UV piezo inkjet technique ranges from 5 to 15 µm, depending on the printing substrate. The dynamic viscosity of these inks ranges from 1 to 30 mPa s. In the piezo inkjet technique, if the drop frequency is defined between 10 and 20 kHz with a drop volume of 14 pL, the drop diameter is approximately 30 µm (Kipphan 2001).

The particular UV curable piezo inkjet printer used in this research has print-heads of 1024 nozzles with a droplet volume of 12 pL for inks with viscosity from 10 to 15 mPa s, which produce high-quality solids and tonal rendering at up to 720 x 1440 dots per inch (dpi). The smallest element of a print generated by an ink jet printer is a dot. To analyze the printing properties of laboratory papers containing straw pulp, a test pattern of six different dot radii (0.35, 0.25, 0.15, 0.125, 0.10, and 0.05 mm) was applied five times on each of the printing papers (Plazonic *et al.* 2014b). The maximum dot radius of 0.35 mm with dot area of 0.385 mm^2 was selected because 50% halftone pattern in prepress (on raster image processor, RIP) contains a dot area of 0.3188 mm when printed with a conventional newspaper press (Dobric *et al*. 2013).

Analysis of Quality Reproduction

The analysis of quality reproduction in observed laboratory papers was based on dot area differences and dot shape descriptors (roundness, aspect ratio, and solidity). The equipment used to measure the quality reproduction of printed dots was a DinoLite digital microscope (Dino-Lite Europe, Naarden, The Netherlands) with 200x magnification. ImageJ software was used for image analysis (measurements and calculations) of dot reproduction. This software is being developed by Wayne Rasband (the Research Services Branch, National Institute of Mental Health, Maryland, USA) and the source code is freely available.

Dot area is defined as a number of pixels located within the boundary of a segmented printed dot and was calculated according to Eq. 3. Area increment, as a dot reproduction attribute, was calculated using Eq. 4,

$$Area = \pi \times radius^2 \tag{3}$$

$$Area\ increment = \frac{Area_{PPS} - Area_{TP}}{Area_{PPS}} \times 100 \tag{4}$$

where $Area_{PPS}$ is the printed dot area on the laboratory paper and $Area_{TP}$ is the dot area defined by the test pattern.

The major axis of an ellipse is the longest diameter that goes through the center and its ends are the widest points of the shape. In addition, the minor axis crosses the major axis in the center and its ends are the narrowest points of the ellipse. Based on these parameters, two additional features, roundness and aspect ratio, *i.e.*, elongation, could define the shape modifications of an ideal dot (Eqs. 5 and 6) (Doyle 2000; Fleming *et al.* 2003).

$$Roundness = \frac{4 \times Area}{\pi \times Major\ Axis^2} \tag{5}$$

$$Aspect\ Ratio = \frac{Major\ Axis}{Minor\ Axis} \tag{6}$$

Solidity (convexity) indicates whether an object has an irregular border or not. That is determined by using the gift wrapping algorithm as an algorithm for calculating the convex area (Eq. 7) (Rodriguez *et al.* 2012).

$$Solidity = \frac{Area}{Convex\ Area} \tag{7}$$

All measurements were repeated 10 times on every laboratory paper containing straw pulp as well as on control paper.

RESULTS AND DISCUSSION

Unprinted Laboratory Papers

The effects of different mixing levels of straw pulps (Table 4) were researched by observing the properties of laboratory papers in comparison to a control sample (N). The results are summarized in Table 5.

Table 5. Unprinted Laboratory Papers Properties

Laboratory Papers	Thickness (µm)	Ash (%)	R_a (µm)	Tensile index(Nm/g)	M_{5min} (%)	CWSN
N	94.0 ± 2.79	4.73 ± 0.22	4.15 ± 0.34	42.34 ± 3.45	171.23	7A
1NW	95.3 ± 2.83	4.14 ± 0.43	4.13 ± 0.43	43.61 ± 2.01	242.21	7A
2NW	98.1 ± 5.28	3.77 ± 0.31	4.24 ± 0.34	41.80 ± 2.40	254.32	7A
3NW	101.5 ± 5.32	3.64 ± 0.07	4.59 ± 0.51	41.02 ± 1.61	268.50	6A
1NB	97.9 ± 3.98	4.12 ± 0.08	4.06 ± 0.36	43.17 ± 2.25	251.38	7A
2NB	98.3 ± 2.58	4.04 ± 0.65	4.23 ± 0.32	42.52 ± 2.15	253.62	7A
3NB	99.1 ± 4.06	3.32 ± 0.67	4.22 ± 0.38	40.31 ± 1.99	256.53	6A
1NTR	96.3 ± 6.35	4.19 ± 0.47	4.25 ± 0.56	44.37 ± 3.77	252.86	7A
2NTR	98.3 ± 6.68	3.89 ± 0.15	4.37 ± 0.34	41.69 ± 1.00	263.26	6A
3NTR	99.4 ± 6.20	3.39 ± 0.15	4.40 ± 0.39	41.15 ± 1.91	264.48	6A

On the basis of these results, it can be concluded that all of the studied straw pulps resulted in laboratory papers having almost equal values in all of the observed properties. Namely, addition of straw pulp to the main recycled newsprint portion produced laboratory papers with higher thickness and surface roughness. On the other hand, tensile index and ash content of laboratory papers were being reduced with higher portion of straw pulp. The surface strength (CWSN value) of the laboratory papers containing straw pulp, were similar to those of the control sheet made by recycled newsprint (CWSN = 7A), except for laboratory papers with 30% of straw pulp (CWSN = 6A). Laboratory papers with different contents of straw pulp showed higher water absorption compared to the control sheet (paper without straw pulp), which is caused by the chemical constituents of the pulp used in forming laboratory papers. Namely, cellulose and hemicelluloses contain numerous accessible hydroxyl groups so they are greatly responsible for the high water absorption of natural fibers. By adding the straw pulp into the recycled newsprint base, that is by increasing its portion, the content of cellulose and hemicelluloses in laboratory papers is increasing and consequently also the water absorption ($M_{\%}$).

The arithmetic mean surface roughness values in all laboratory papers were very similar (ranging from 4.06 to 4.58 µm), whereby the addition of 30% straw pulp increased the paper roughness. These results were expected because the addition of straw pulp reduced the amount of additives and fillers originating in the pulp from Commercial UPM News C paper, which was used as a basic component of laboratory papers ($ash_{\%}$ =10.00 ± 0.04; presented in Table 3).

Printed Laboratory Papers

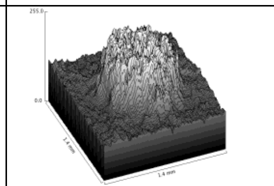
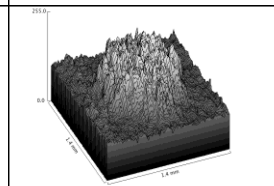
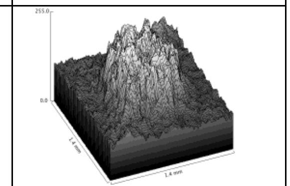
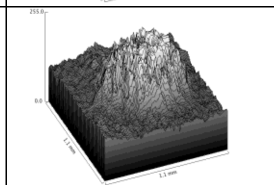
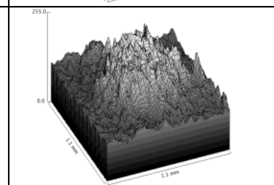
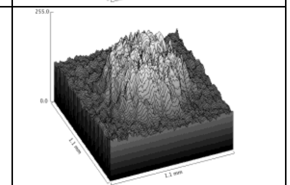
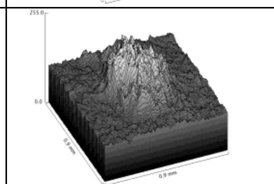
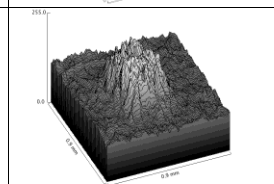
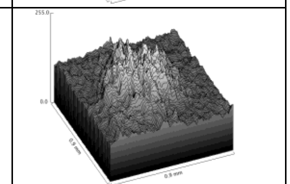
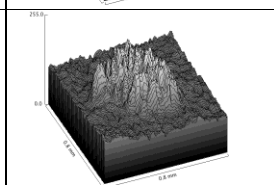
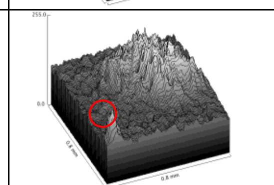
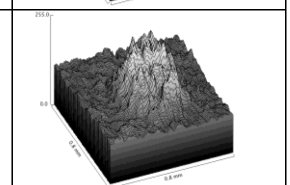
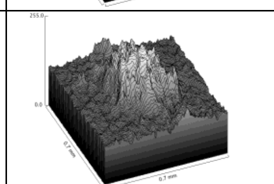
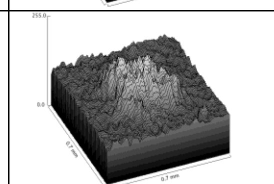
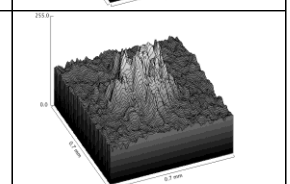
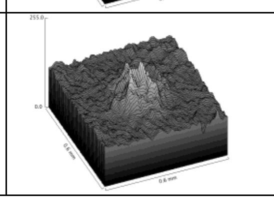
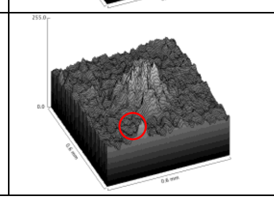
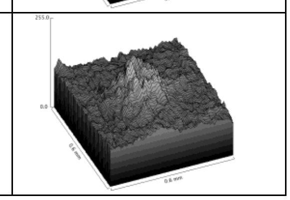
3D surface plots diagrams of all dots defined by test pattern applied by UV-curable ink jet printer on laboratory papers containing 70% newsprint and 30% straw pulp are presented in Table 6.

An ideal dot reproduction is envisaged as a perfect sharp circle without any mechanical gain and of consistent density (Fleming *et al.* 2003). The printing process commonly generates a dot gain as a result of printing pressure, ink viscosity, or the type of substrate used for printing (Brody and Marsh 1997). Each printing process deforms dots defined by test pattern. Ideal dot reproduction is impossible; therefore they appear larger than their initial size (Bates *et al*. 2014; Plazonic *et al*. 2014b). The research presented in this paper explains the occurrence of deviancies of printed dots from the ideal (initial) dot defined by the test pattern.

Dot reproduction on laboratory papers was researched for the purpose of establishing the most suitable weight ratio of straw pulp in papers, which is necessary for achieving good reproduction quality. In digital printing processes, the images of printed dots have background noise. That appearance is caused by the presence of a uniform distribution of a very small quantity of satellite ink or dye droplets in the non-image area (Oliver and Chen 2002). The presence of droplets were clearly observed on 3D surface plots diagrams near the dot r = 0.125 mm on paper 3NB and dot r = 0.05 mm on paper 3NB (presented in Table 6 - marked with red circles).

The dot area increment in relation to the printed dot radius on a control paper and printing paper containing wheat, barley, and triticale pulp are presented in Figs. 3 through 5. The evaluated laboratory papers followed similar trends when the dot area was increased (from 38.48% to 600.28%) by decreasing the defined dot radius in a test pattern. Comparing a control paper against papers that contain barley or triticale pulp, the analysis registered similar or equal area increments, while the presence of wheat pulp in papers provided lower area increments in the largest printed dots (defined dot r = 0.35 and 0.25 mm).

Table 6. 3D Surface Plots Diagrams of Laboratory Papers Containing 30% Straw Pulp

Radius of printed dots (mm)	3D surface plots diagrams		
	3NW	3NB	3NTR
0.35			
0.25			
0.15			
0.125			
0.10			
0.05			

The effect of type and quantity of straw pulp in papers was noticeable in the smallest dots with a radius of 0.050 mm, especially on papers containing wheat (Fig. 3) and barley pulp (Fig. 4), where dot areas were reduced compared to the control sample (area increment = 553.59%).

The effect of straw pulp in printing paper on the dot reproduction in relation to the printed dot radius was also analyzed based on the dot shape descriptors (Fig. 6). Evaluation of dot shape descriptors included analysis of roundness, solidity, and aspect ratio. Roundness and aspect ratio parameters describe the shape modification of an ideal dot, with the values for an ideal printed dot being 1 (Fleming *et al.* 2002, 2003; Stančić *et al.* 2012). The parameter solidity describes the regularity of a dot border and also has a value of 1 in an ideal dot reproduction.

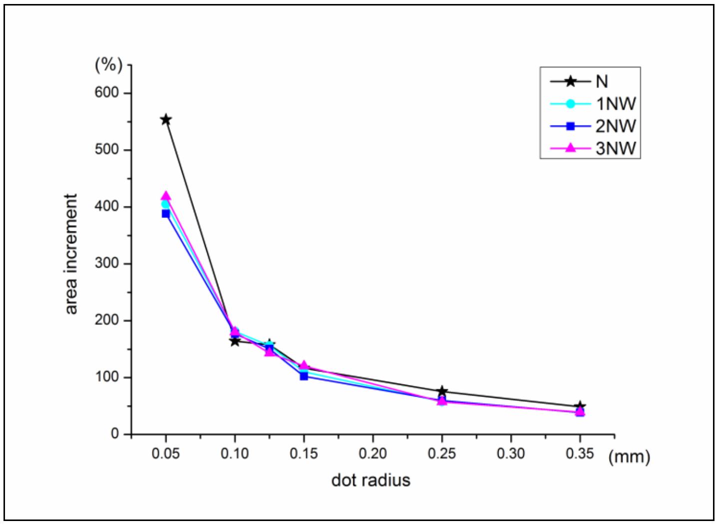


Fig. 3. Dot area increment on laboratory papers with wheat pulp and control sample

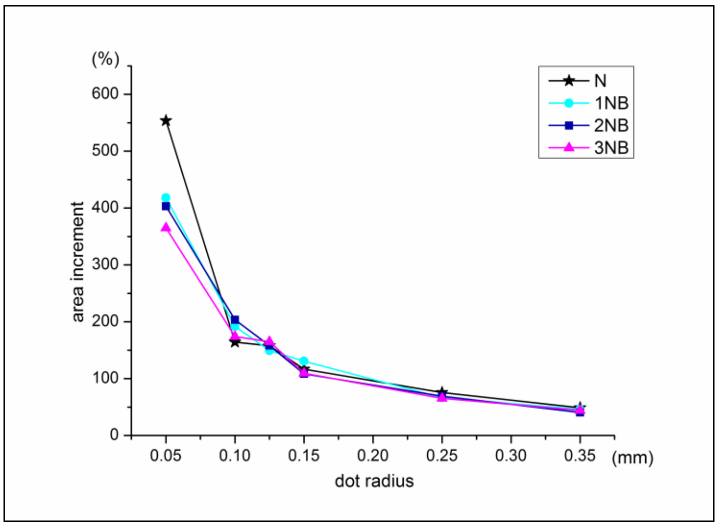


Fig. 4. Dot area increment on laboratory papers with barley pulp and control sample

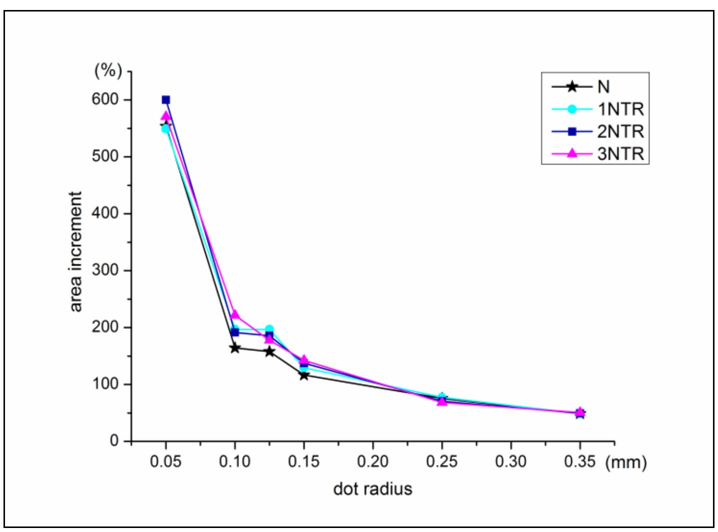


Fig. 5. Dot area increment on laboratory papers with triticale pulp and control sample

The results presented in Fig. 6 show that the laboratory paper composition had no noticeable impact on any of the evaluated shape descriptor values in the largest printed dots (r = 0.35, 0.25, and 0.15 mm). The type and the quantity of straw pulp in printing paper affected all shape descriptors in the smallest dots (r = 0.125, 0.10, and 0.05 mm), especially the aspect ratio values. In all observed laboratory papers, the roundness values were close to 1 in the largest printed dots (mean roundness for dots: r = 0.35 mm was 0.918 ± 0.014; r = 0.25 mm was 0.889 ± 0.016; r = 0.15 mm was 0.862 ± 0.027).

Furthermore, for small printed dots, the roundness values decreased (mean roundness for dots: r = 0.125 mm was 0.802 ± 0.042; r = 0.10 mm was 0.787 ± 0.028; r = 0.05 mm was 0.730 ± 0.084). After having observed each dot size, it could be concluded that values for roundness were similar in all analyzed laboratory papers. These values decreased with decreasing dot radius. The least round dots were those with a 0.05-mm dot radius (Fig. 6f). Solidity values followed similar trends for evaluated laboratory papers as roundness values (mean solidity for dots: r = 0.35 mm was 0.882 ± 0.011; r = 0.25 mm was 0. 857 ± 0.012; r = 0.15 mm was 0.841 ± 0.015; r = 0.125 mm was 0.818 ± 0.030; r = 0.10 mm was 0.810 ± 0.018; r = 0.05 mm was 0.736 ± 0.028). Results of aspect ratio (AR) measurements indicted that dots with higher radius had values of nearly 1. The values of AR increased with decreasing dot radius (values varying from 1.07 to 1.81). The aspect ratio values measured in dots with higher radius were not affected by the composition of laboratory papers (Figs. 6a through 6c). This was not the case in dots with smaller radii (Figs. 6d through 6f), especially for the dot r = 0.05 mm, where the AR values were different when compared against a control sample made only of recycled newsprint (N).

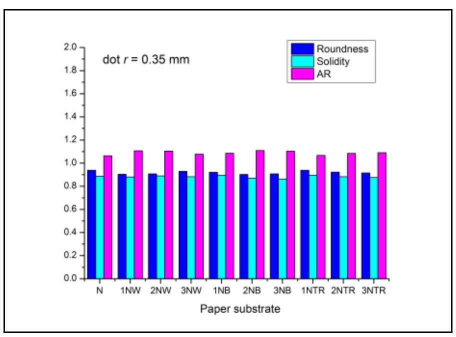


Fig. 6 a. Shape descriptors of dot radius 0.35 mm

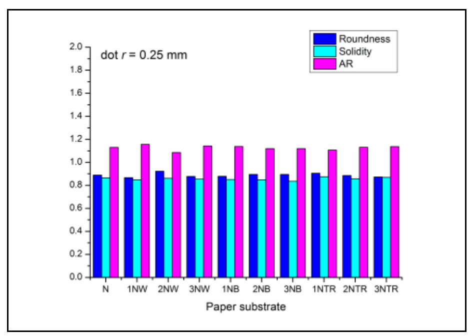


Fig. 6 b. Shape descriptors of dot radius 0.25 mm

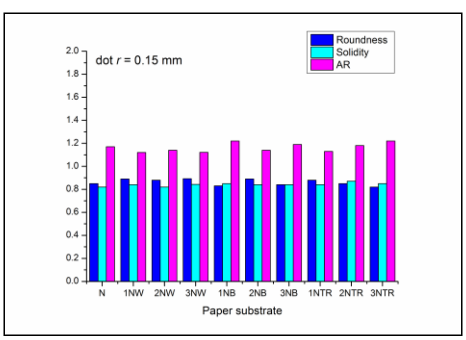


Fig. 6 c. Shape descriptors of dot radius 0.15 mm

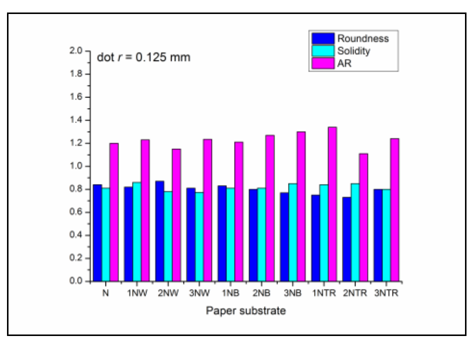


Fig. 6 d. Shape descriptors of dot radius 0.125 mm

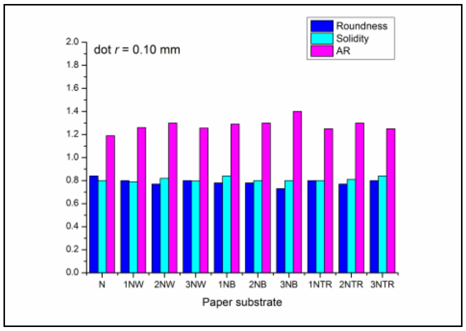


Fig. 6 e. Shape descriptors of dot radius 0.10 mm

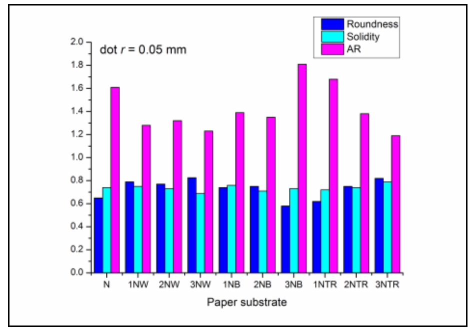


Fig. 6 f. Shape descriptors of dot radius 0.05 mm

Based on these results, it could be concluded that the straw pulps are a potential replacement for recycled fibers when forming laboratory papers. It is well known that commercial papers produced in industrial production have better optical, physical, and mechanical properties compared to the laboratory-formed papers. To confirm this, additional analysis of dot reproduction quality on commercial newspapers were performed. By its origin, fibers used in laboratory formed control papers (marked N) and commercial UPM News C papers are recycled wood fibers. Observing roughness as a physical paper property of commercial newspaper and laboratory-formed control papers (N), it was confirmed that the laboratory-formed paper was rougher (Table 5) than the commercial newspaper (Table 3). Differences were very high (ΔR_a MD = 1.579; ΔR_a CD = 0.989), especially when the roughness of laboratory-formed paper (N) and roughness of commercial newspaper measured in a machine direction had been compared. This was a result of fiber orientation in the laboratory papers. Because of the process of forming paper sheets, fibers in the laboratory-formed papers were arbitrarily oriented. The conditions of fiber arrangement and interweaving strongly affect the paper surface, which generate reproduction quality of printing paper.

Dot reproduction quality of commercial newspaper is presented in Figs. 7 and 8. It could be concluded from Fig. 7 that the dot area increment in all analyzed dots on commercial newspapers was smaller than in all laboratory-formed papers. The properties of paper surface had the strongest impact on the reproduction quality of small printed dots.

If all dots would be observed, the difference of dot area increment in commercial newspapers compared to laboratory-formed control samples would be smallest in dots with radius 0.35 mm (Δ area increment $_{0.35}$ = 4.09) and it would increase as the dots become smaller (Δ area increment $_{0.05}$ = 144.30). As expected, commercial newspaper had better reproduction quality of dots, taking into account shape descriptor results (Fig. 8). In particular, the roundness, solidity, and AR values of printed dots on commercial newspaper were closer to 1, which is defined as the value of an ideal dot reproduction. Evaluated shape descriptor values of dots printed on commercial newspaper follow similar trends as the dot area increment results.

The differences of all shape descriptor values between commercial newspapers and laboratory-formed control samples were increased with the decreasing defined dot radius in a test pattern (Δ roundness from 0.030 to 0.048; Δ solidity from 0.025 to 0.041; Δ AR from -0.014 to -0.038).

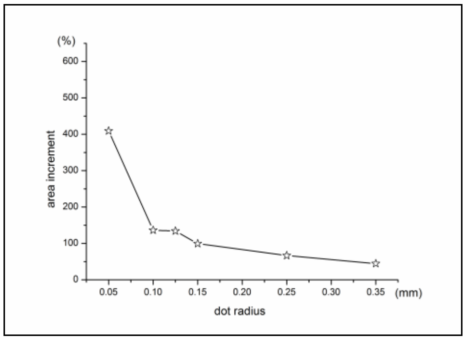


Fig. 7. Dot area increment on commercial newspaper

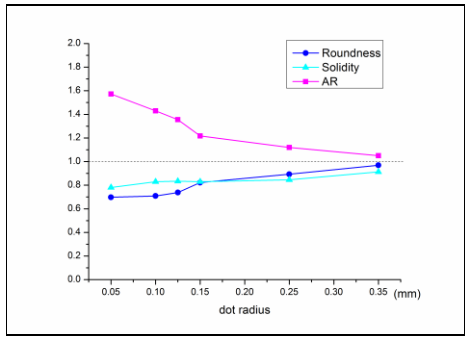


Fig. 8. Shape descriptors values on commercial newspaper

The results obtained in this research suggest that the reproduction quality of laboratory papers formed of straw pulp could be additionally improved if the papers would be formed in industrial production.

CONCLUSIONS

On the basis of data obtained from the researched effects of straw pulp in printing papers on the dot reproduction attributes, the following conclusions can be drawn:

1. The weight ratio of straw pulp in laboratory papers had no significant impact on the reproduced dot area and the shape of large dots (r = 0.35, 0.25, and 0.15 mm), while its impact became evident in small dots (r = 0.125, 0.10, and 0.05 mm).
2. Wheat pulp in laboratory papers provided a slightly better reproduction quality compared to barley and triticale pulp content.
3. The piezo ink jet printing process and raster image processor (RIP) are unable to reproduce dots below r = 0.10 mm, which has been confirmed by observing area increment results on commercial newspaper.
4. The results of the dot reproduction analysis verified that straw pulp (wheat, barley, and triticale) in printing papers provided equal or even better paper printing quality than recycled newsprint. Therefore, straw pulp could be used for certain categories of printing papers.

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