This paper investigates the quality of inkjet printing on corrugated cardboard with various characteristics such as the presence of surface coating, the type of cardboard structure, the corrugated layer profile, and the corrugated cardboard height.

The color characteristics of the corrugated board surface of studied samples were analyzed in the CIE Lab system; the value of the discrepancy in the shade of white was established when compared with the reference values of the ISO 12647 standard.

During the study, the main criteria for assessing the quality of color reproduction of inkjet imprints were analyzed: an indicator of the general contrast level (K), the value of color differences for the basic tone shades (ΔE), and the volume of the body color coverage (ΔE^2).

It was found that when printing on various types of corrugated cardboard, there is a general decrease in the overall contrast value. The actual level of color differences is ΔE=10...45 and exceeds the permissible standards for the color reproduction quality. This adversely affects the reproduction of different color tones in the printed image. In general, the quality of color reproduction differs for the test samples of corrugated cardboard in terms of the magnitude of the spread in the values of color distortions on the tone shades.

The influence of the main characteristics of the investigated samples of corrugated cardboard on the quality indicators of inkjet printing has been analyzed. In particular, a significant influence of the index of color characteristics of the surface of corrugated cardboard L^* and the type of corrugated board structure on the quality of color reproduction has been established.

The study results reported here could make it possible to reasonably approach the selection of the corrugated board structure that is optimal in composition, increase the productivity of the technological process for manufacturing containers, and stabilize the quality of printing on corrugated cardboard

Keywords: corrugated cardboard, color differences, printing contrast, inkjet printing, quality of the imprint

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INFLUENCE OF THE SURFACE CHARACTERISTICS OF CORRUGATED CARDBOARD ON THE QUALITY OF INKJET PRINTING

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1. Introduction

The use of digital printing for the manufacture of printed products continues to grow due to the possibility of printing on various types of materials. In addition to classic printing editions such as books, magazines, and advertising products, digital printing on packaging is quite actively used. It is relevant to print on the surface of corrugated cardboard using digital inkjet printing. In particular, the development of new digital technologies [1] has allowed using inkjet printing on the surface of a wide range of existing types of corrugated cardboard.

The main limitation when using inkjet printing on corrugated cardboard is the low quality of color reproduction on the imprint. This is due to the relatively lower optical and printing-technical surface properties for most types of corrugated cardboard. As there are many technologies for making corrugated cardboard, the characteristics of its surface can have different effects on the imprint's quality. It should also be noted that the tolerances on the printing quality on various materials according to ISO 12647 [2] are adapted to the standard range of printing paper. Therefore, a comprehensive study of the effect of surface characteristics of different types of corrugated cardboard on the quality of inkjet imprints is an important scientific area. The results to be obtained would make it possible to establish acceptable tolerances on the quality of color reproduction on inkjet imprints for different types of corrugated cardboard. It is especially important to establish the types of corrugated cardboard with stable color reproduction when printing.

2. Literature review and problem statement

The quality of color reproduction on the surface of corrugated cardboard when using offset and flexographic printing

can be improved through the process of lamination [3], or the use of micro corrugated cardboard [4]. However, these approaches increase the cost of production and limit the range of packaging manufacture. So, each type of printed material has limitations on the accuracy of color reproduction depending on the printing modes and methods.

Paper [5] reports the results of studying the quality of the offset printing process on standard types of paper, which differ in the characteristics of the printed surface. The authors found a significant correlation between the surface characteristics of the printed material and the imprint quality, which could optimize the printing process. A similar approach was used in another work [6], whose authors investigated the quality of flexographic printing for packaging. The regularities of the influence of the characteristics of the studied consumables established in [7] made it possible to devise basic recommendations for improving the quality of offset and flexographic printing. The authors of [8] determined that for digital inkjet printing, it is critical to control the level of color distortion, which is crucial to ensure high-quality color reproduction on imprints. Thus, the cited studies [3–8] mainly reflect the features in the influence of the surface characteristics of corrugated cardboard under standard printing conditions, which are regulated by standards [2].

Inkjet printing makes it possible to obtain imprints on a wide range of printed materials. The possibilities of inkjet printing on various materials have been studied in recent years in a large number of scientific papers. In particular, in [9], the regularities of the influence of the surface characteristics of non-absorbing materials on the quality of inkjet printing were established. In [10], the authors proposed a method for determining the dynamics of water penetration into the paper structure, which allowed establishing the suitability of materials for inkjet printing. The authors of [11] tested a procedure of assessing the quality of digital and offset printing on corrugated cardboard. In [12], the authors investigated the quality of gradation transfer on different grades of corrugated cardboard with a comparison of offset and digital printing. However, the results reported in [9–12] make it possible to establish only the general patterns of the impact of the printed material characteristics on the quality of inkjet imprints.

Also, it is important to select methods for analyzing the quality of color reproduction on imprints when studying various indicators of the printed material. Thus, in [13], the authors compared the suitability of different quality control methods for stabilizing the inkjet printing process. The authors of [14] found a significant influence of structural properties, in particular, the non-uniformity of the surface of consumable material on the qualitative characteristics of imprints. The authors of [15] established the influence of the physical and optical parameters of consumables at different digital printing technologies on imprint quality. In particular, the authors determined lower quality indicators of inkjet printing compared to electrophotographic. In addition, the authors revealed a tendency to reduce the quality of printing on the surface of consumables made with the addition of recycled materials. In [16], the authors proposed new approaches to study the quality of color reproduction of inkjet imprints using special modes of preparation of the original layout, which could stabilize the quality of imprints and reduce the consumption of inks. The authors of [17] determined the patterns of interaction of the ink layer with the surface of various printed materials when using inkjet printing.

Thus, available studies into the color reproduction quality on the surface of corrugated cardboard are mainly related to the classical methods of offset and flexographic printing. Research on the quality of color reproduction on inkjet imprints concerns the analysis of general issues of color reproduction on standard types of printed material. In particular, in the cited studies, there is no comprehensive comparison of imprints obtained on corrugated cardboard of different types depending on such a qualitative indicator as the printing contrast and the amount of color coverage of imprints. These indicators are important in assessing the suitability of corrugated cardboard for quality printing.

Therefore, to establish the possibility of using different types of corrugated cardboard for inkjet printing, it is necessary to address the issue related to the impact of surface characteristics of different types of corrugated cardboard on the quality of color reproduction on imprints. That could make it possible to reasonably select the optimal composition of the corrugated cardboard in order to stabilize the quality of color reproduction on inkjet imprints.

3. The aim and objectives of the study

The study aims to establish the influence of surface characteristics of different types of corrugated cardboard on the quality of color reproduction on digital inkjet imprints. That would make it possible to reasonably select the optimal composition of the corrugated cardboard to stabilize the quality of color reproduction on imprints.

The following tasks were set to accomplish this aim:

– to analyze the color characteristics of surface on different types of corrugated cardboard;

– to determine the level of general imprint contrast in the inkjet printing on different types of corrugated cardboard;

– to determine the level of color distortion on the imprints of corrugated cardboard;

– to determine the amount of color coverage of inkjet imprints on different types of corrugated cardboard;

– to determine the influence of the main characteristics of the studied samples of corrugated cardboard on the quality of inkjet printing.

4. The study materials and methods

4. 1. The studied materials and tools

This study analyzed the imprints obtained at the digital inkjet printing machine Barberan Jetmaster 1890 (Spain), which has such characteristics as a resolution of 360 dpi, a print width is up to 1890 mm, and the productivity of up to 50 m/min [18].

The list of characteristics of the studied samples of corrugated cardboard is given in Table 1.

The range of corrugated cardboard used during our study differed in type (three- and five-layer), the profile of the corrugated layer (*B, C, E,* and their combinations), and the presence of a special surface coating (Fig. 1).

The samples of the materials selected for our study are represented by common types of corrugated cardboard (Table 1), which is a typical range in the manufacture of packaging.

Table 1

Characteristics of the studied samples of corrugated cardboard

No.	Corrugated cardboard	Lacquer on surface	Corrugated board structure type (the number of layers)	Profile of corrugated layer	Board height, mm
1	Sample 1 (S1)	Yes	5	EB	4
2	Sample 2 (S2)	Yes	5	EB	4
3	Sample 3 (S3)	No	5	EB	4
4	Sample 4 (S4)	Yes	5	EB	4
5	Sample 5 (S5)	No	5	EB	4
6	Sample 6 (S6)	Yes	3	B	2.5
7	Sample 7 (S7)	Yes	3	B	2.5
8	Sample 8 (S8)	Yes	3	EC	4.5
9	Sample 9 (S9)	No	3	E	2.5
10	Sample 10 (S10)	yes	3	E	2.5
11	Sample 11 (S11)	yes	3	E	1.3
12	Sample 12 (S12)	yes	3	B	3
13	Sample 13 (S13)	yes	5	C	4
14	Sample 14 (S14)	yes	5	EB	4
15	Sample 15 (S15)	yes	5	BC	7
16	Sample 16 (S16)	yes	3	C	4
17	Sample 17 (S17)	yes	3	E	3

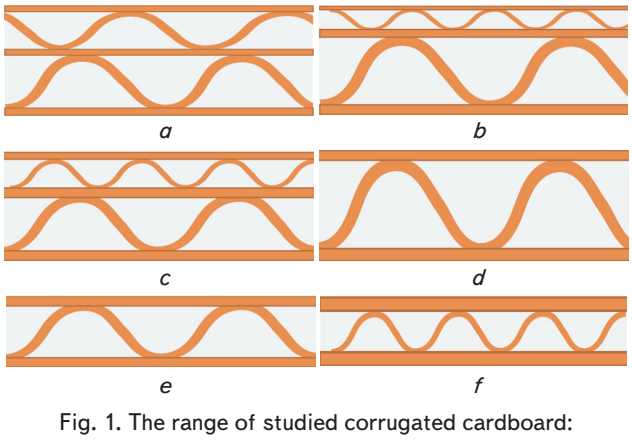

Fig. 1. The range of studied corrugated cardboard: *a* — five-layer with the BC profile; *b* — five-layer with the EC profile; *c* — five-layer with the EB profile; *d* — three-layer with the C profile; *e* — three-layer with the B profile; *f* — three-layer with the E profile

4. 2. Research methodology

During our work, the color characteristics of different types of corrugated cardboard used for colorful printing using inkjet digital printing were analyzed. Measurement of color characteristics was performed according to standard methods [19] and on corrugated cardboard printed samples using the X-Rite SpectroEye spectrophotometer (USA) [20]. The analysis of the measured color characteristics was carried out according to the established requirements by the ISO 12647 standard on color reproduction quality [2]. Statistical data processing was performed using the software packages MS Excel (USA) and MathWorks MATLAB (USA).

The criteria we used for assessing the quality of color reproduction of digital inkjet imprints were as follows: the indicator of the level of total contrast (1), the magnitude of color differences for the main shades (2), and body volume color coverage (3) based on a^*b^* coordinates in the CIE Lab color system [19]:

$$C = \frac{D_S - D_T}{D_S} \times 100, \quad (1)$$

$$\Delta E_{a^*b^*} = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}, \quad (2)$$

$$G = \frac{1}{2}\left|\sum_{i=1}^{n-1} a_i^* b_{i+1}^* + a_n^* b_1^* - \sum_{i=1}^{n-1} a_{i+1}^* b_i^* - a_1^* b_n^*\right|, \quad (3)$$

where ΔL^* is the difference of lightness value between the standard and an imprint; Δa^* is the difference in coordinates of the color component a^* between the standard and an imprint; Δb^* is the difference in coordinates of the color component b^* between the standard and an imprint; D_S is the solid tone color; D_T is the tone color on 75 % of the printed area; a_i^*, b_i^* are the color coordinates of the CIE LAB system for the process (CMY) and binary (RBG) colors of solids on the imprints; G (ΔE^2) is the body volume of color coverage.

5. Results of studying the influence of the surface properties of corrugated cardboard on the quality of inkjet imprints

5. 1. Determining the surface color characteristics on various types of corrugated cardboard

The quality of color reproduction on imprints depends on both the physical and optical properties of the surface of the printed material. In this work, the optical properties of different types of corrugated cardboard have been analyzed. In particular, we tested the compliance of the optical properties of the corrugated board surface with the existing requirements of the ISO 12647 standard, which determines the tolerances for deviations in color characteristics measured on the corrugated board surface (Fig. 2).

Analysis of color coordinates by the shade of white for the surface of corrugated cardboard allowed us to establish (Fig. 2) that the studied samples can be divided into two groups W_0 and W_1. The first group W_0, which has a relatively slight difference in white color from the five types of printed paper according to ISO 12647, includes samples of corrugated cardboard: S1–S6, S11, S15–S17. The second group W_1, which has a relatively large difference in white color from the five types of printed paper according to ISO 12647, includes samples of corrugated cardboard: S7–S10, S12–S14. A significant difference in the hue of the tone on the surface of corrugated cardboard from a neutral white tone, can affect the accuracy of color reproduction and reduce the number of tone gradations on the imprints.

Also, to analyze the surface of corrugated cardboard, for each sample we measured lightness (L^*) in the CIE Lab system (Fig. 3). Analysis of the lightness results indicates that only the sample of corrugated cardboard S11 fully meets the requirements of ISO 12647. All other samples of corrugated cardboard can be divided into two groups. The first includes samples of corrugated cardboard S1–S6 and S15–S17,

which have a slight deviation in lightness. The second group includes samples of corrugated cardboard S7–S10 and S12–S14, which have a relatively higher deviation in lightness.

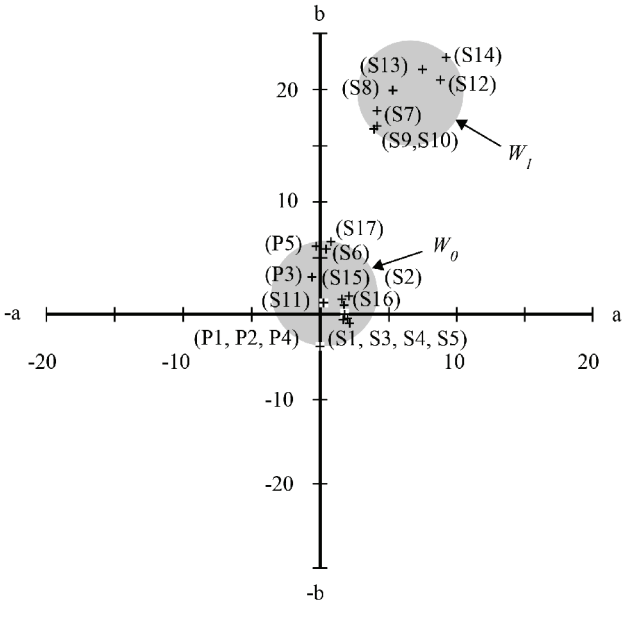

Fig. 2. Surface color characteristics of the corrugated cardboard based on a^*b^* coordinates of CIE LAB system: W_0 – corrugated cardboard with slight color deviations in the shade of white; W_1 – corrugated cardboard with significant color deviations in the shade of white; P1, P2, P3, P4, and P5 – color coordinates by the shade of white for five types of printed paper according to ISO 12647; S1, S2, S3...S17 – color coordinates by the shade of white for the investigated samples of the corrugated cardboard by its sequence number (Table 1)

According to the results of measuring the color characteristics of the corrugated cardboard surface and the requirements of ISO 12647, more suitable for quality color reproduction are the samples of the first group W_0 (Fig. 2). In particular, samples S1–S6, S11, and S15–S17 are characterized by slight deviations in the values of color characteristics of the printed surface (Fig. 2, 3).

5. 2. Determining the overall contrast for inkjet imprints on various types of corrugated cardboard

During the study, the overall printing contrast for inkjet imprints on different samples of corrugated cardboard was analyzed (Fig. 4), which was calculated based on (1).

The overall contrast indicator should be in the range of 0.25...0.50 [21], which would allow the imprints to reproduce the shades correctly in the middle tones, as well as affect the accuracy of color reproduction. In general, the overall contrast of printing for the studied samples of corrugated cardboard is within acceptable limits. Slightly reduced print contrast is typical of samples S3 and S9 (Table 1).

5. 3. Determining the level of color distortion on corrugated cardboard imprints

The main indicator of the quality of color reproduction on imprints is the calculation of the magnitude of color differences (ΔE), the value and tolerances for which are specified by the standard ISO 12647 [2]. Usually, the magnitude of color differences is measured using spectrophotometric measurements on special test fields with spot tones of different shades. Therefore, to determine the quality of color reproduction on inkjet imprints, we measured the basic (CMY), binary (RGB), and achromatic (BW) hue tones on dies using the X-Rite SpectroEye spectrophotometer (USA). To analyze the overall level of color differences, statistical processing of the measured data for each imprint was used by calculating the following indicators: median, upper, and lower quartiles, and an interquartile range [22]:

$$Q_p = \left(1-\left(x-i\right)\right)\cdot A_i + \left(x-i\right)\cdot A_{i+1}, \quad (4)$$

$$K_{IQR} = Q_3 - Q_1, \quad (5)$$

where Q_p is a quartile, at $p=0.25$ – the first quartile (Q_1), at $p=0.5$ – median, at $p=0.75$ – the third quartile (Q_3); x is the quartile index, i is the element index in the ordered sample; A_i, A_{i+1} are the elements of a random sample; K_{IQR} is the interquartile range.

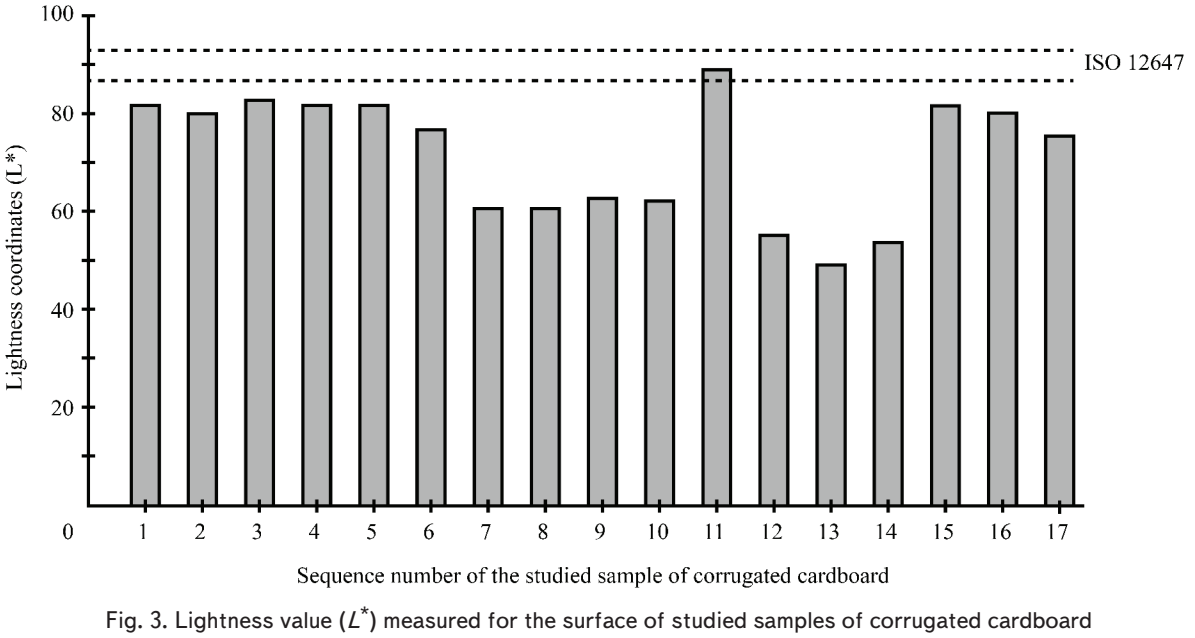

Fig. 3. Lightness value (L^*) measured for the surface of studied samples of corrugated cardboard

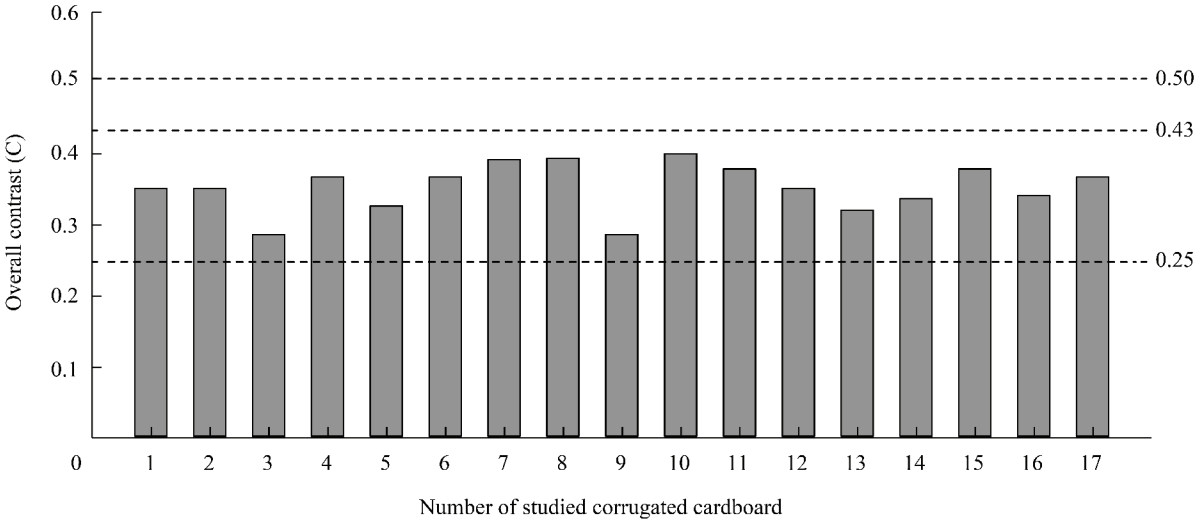

Fig. 4. Overall printing contract (C) for inkjet imprints on the studied samples of corrugated cardboard

The analysis of the general level of color distortions (ΔE) for inkjet imprints was conducted according to the constructed range diagram (Fig. 5). Our analysis of the range diagram (Fig. 5) reveals a slight decrease in the quality of color reproduction on imprints compared to the requirements set by ISO 12647 [2].

The level of color distortion (ΔE) on the imprints for all investigated samples of corrugated cardboard is twice higher than recommended according to ISO 12647 [8].

On the range diagram (Fig. 5), there is a significant dependence of the total level of color distortion (ΔE) of the imprints on the value of lightness (L^*) of the unprinted surface of the studied samples of corrugated cardboard (Fig. 3). This confirms the significant influence of the characteristics of the surface of corrugated cardboard on the quality of color reproduction in the printing process. In particular, larger color distortions for all shades of tone with a significant scatter of color distortion values (Fig. 5, samples S7–S10 and S12–S14) are characteristic of corrugated cardboard samples with lower surface color characteristics.

5. 4. Analysis of color coverage of inkjet imprints on different types of corrugated cardboard

During our study, the color coverage in the CIE Lab system for inkjet imprints of the investigated samples of corrugated cardboard was analyzed, which were compared with the color coverage plots for reference imprints [2].

Analysis of the color coverage of inkjet imprints on different types of corrugated cardboard revealed the predicted effect of the overall level of color distortion (ΔE) on the reduction of color coverage.

Most of the imprints of the studied samples of corrugated cardboard generally provide color coverage at the level of the reference imprint with low requirements for color reproduction.

To quantify the amount of color coverage by CIE Lab coordinates of primary (CMY) and binary (RGB) colors, expression (3) was used to calculate the square of the 2D figure of color coverage (Fig. 6). Fig. 6 shows the total area of the 2D color coverage figure of inkjet imprints for the studied samples of corrugated cardboard, which confirms the results of color reproduction analysis and points to 7 samples with insufficient color coverage. In particular, the total area of the 2D figure of the color coverage for half of the studied samples is reduced almost twice and is G=2,000...4,000 ΔE^2 (Fig. 6, S7–S10 and S12–S14). But the imprints of other samples of corrugated cardboard are characterized by color coverage at the level of the reference imprint according to ISO 12647, which is about G=6,000...8,000 ΔE^2 (Fig. 6, S1–S5, S11, S15, 16).

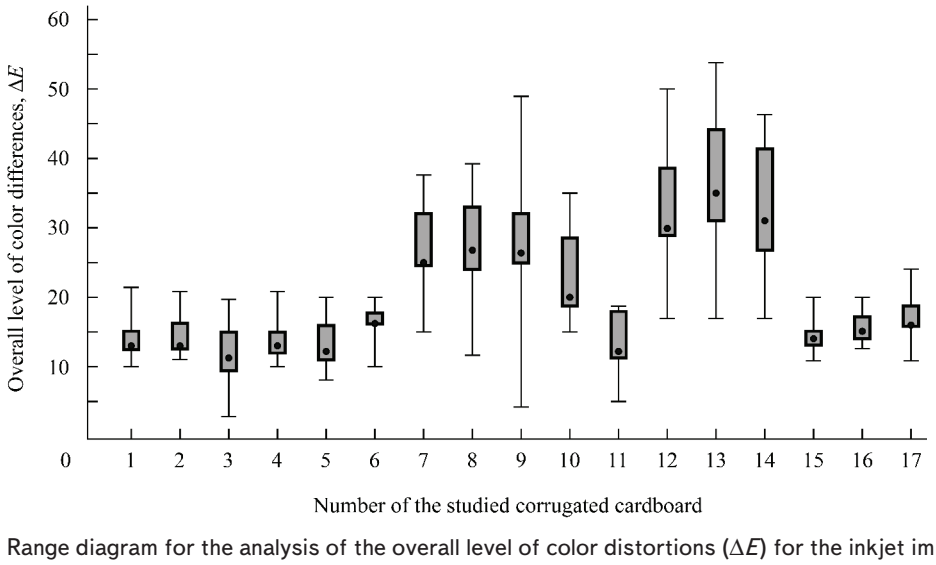

Fig. 5. Range diagram for the analysis of the overall level of color distortions (ΔE) for the inkjet imprints on the studied corrugated board

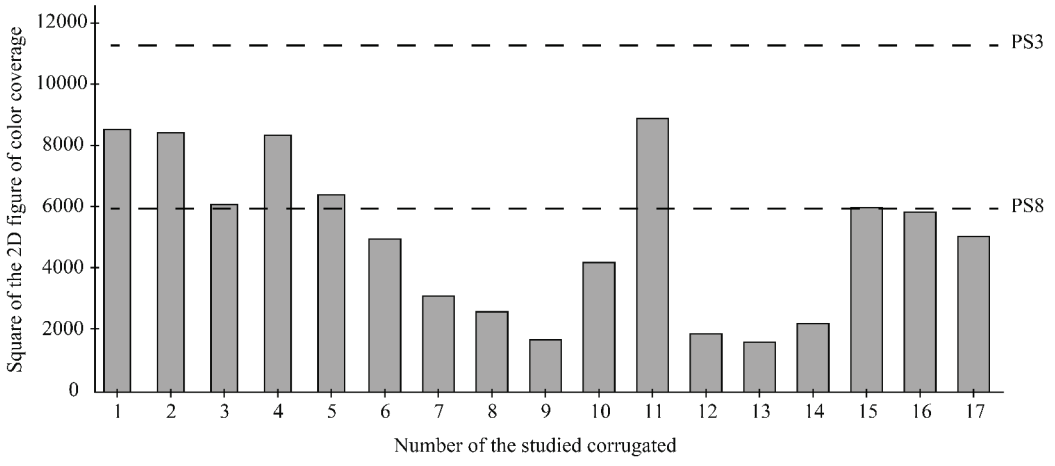

Fig. 6. Histogram with the size of the area of a 2D figure of color coverage: Sample 1...17 – inkjet imprints for the studied samples of corrugated cardboard; PS3 – reference imprint with high requirements to color reproduction according to ISO 12647; PS8 – the reference imprint with low requirements to color reproduction according to ISO12647

5. 5. Determining the influence of the main characteristics of studied samples of corrugated cardboard on the quality of inkjet prints

To determine the influence of the main characteristics of the studied samples of corrugated cardboard on the quality of inkjet printing (Table 2), the correlation analysis of our data was performed [22–24]:

$$R=\sqrt{\frac{\hat{A}^T X^T Y}{Y^T Y}}\cdot\frac{n-1}{m-1}, \tag{6}$$

$$F_R=\frac{R^2}{1-R^2}\cdot\frac{n-m-1}{m}, \tag{7}$$

$$t=\frac{R^2(n-k)}{(1-R^2)(k-1)}, \tag{8}$$

where R is the coefficient of multiple correlation in matrix form, which is a relative measure of the relationship between two parameters with a variation in the value within $-1<R<1$ (for $R>0$, the relationship between X and Y is called positive; for $R<0$, the relationship between X and Y is called negative); X_i, Y_j are the signs of the process between which one must determine the relationship; n is the number of observations; m is the number of independent variables; R^2 is a coefficient of determination; F_R is the statistical significance of the coefficient of determination by the F-criterion; t is the statistical significance of the multiple correlation coefficient by t-statistics.

Table 2

Studied characteristics (x_i) of corrugated cardboard and quality indicators (y_i) of inkjet printing

No.	Corrugated cardboard	x_1, (surface lightness of corrugated board)	x_2, (structure type of corrugated board, the number of layers)	x_3, (height of corrugated board)	y_1, (printing contrast)	y_2, (color distortion)	y_3, (color coverage)
1	Sample 1 (S1)	82	5	4	0.35	14	8,558
2	Sample 2 (S2)	81	5	4	0.35	15	8,454
3	Sample 3 (S3)	83	5	4	0.29	14	6,115
4	Sample 4 (S4)	82	5	4	0.37	14	8,377
5	Sample 5 (S5)	82	5	4	0.33	15	6,437
6	Sample 6 (S6)	78	3	3	0.37	17	4,998
7	Sample 7 (S7)	61	3	3	0.39	27	3,138
8	Sample 8 (S8)	61	3	5	0.39	28	2,624
9	Sample 9 (S9)	64	3	3	0.29	28	1,710
10	Sample 10 (S10)	62	3	3	0.4	24	4,229
11	Sample 11 (S11)	89	3	1	0.38	13	8,927
12	Sample 12 (S12)	56	3	3	0.35	13	1,907
13	Sample 13 (S13)	49	5	4	0.32	37	1,642
14	Sample 14 (S14)	54	5	4	0.34	14	2,237
15	Sample 15 (S15)	82	5	7	0.38	14	6,024
16	Sample 16 (S16)	80	3	4	0.34	15	5,874
17	Sample 17 (S17)	76	3	3	0.37	18	5,079
Average value		71.88	3.94	3.58	0.35	18.82	5,078
Variance		148.34	1	1.44	0.001	48.5	6,202,575

Using expression (6), the correlation matrix was calculated based on normalized data (Table 3). Also, according to expressions (7) and (8), the statistical significance of the coefficient of determination by the *F*-criterion and the multiple correlation coefficient by *t*-statistics were calculated.

Based on the partial correlation coefficients, the value of Student's *t*-criteria was calculated (Table 4), as well as the tabular value of Student's *t*-criterion, which was 2.201. Based on the comparison of the actual values of the *t*-criteria with the critical value of the Student's criterion, it is possible to argue about the existence of multicollinearity between x_1 and y_3, x_2 and y_3, as well as x_3 and y_1. Thus, all the studied characteristics (x_i) of corrugated cardboard have different levels of influence on the quality indicators (y_j) of inkjet printing. Especially large influence is observed between x_1 and y_3, which is explained by the significant influence of color characteristics of the corrugated cardboard surface (lightness index, L^*) on the quality of color reproduction (color coverage, ΔE^2) according to ISO 12647 [2].

Also, a slightly lower effect is observed between the quality of color reproduction and the type of cardboard structure, which can be explained by the use of less amount of secondary raw materials in the manufacture of certain types of corrugated cardboard. All other characteristics and qualitative indicators have insignificant mutual influence.

6. Discussion of results of studying the influence of surface corrugated cardboard characteristics on the quality of inkjet imprints

According to the results of our study, it was found that the quality of color reproduction on the surface of corrugated cardboard by inkjet printing methods is somewhat inferior to the imprints obtained by offset printing methods. Inkjet imprints on different types of corrugated cardboard are characterized by a general decrease in the quality of color reproduction. This is due to the inconsistency of the color characteristics of the surface of different types of corrugated cardboard (Fig. 2, 3) with the requirements of ISO 12647.

The established total contrast of the print (Fig. 4) for samples is in the range between the medium and low levels and is $K=0.3...0.4$.

Also, on most imprints of corrugated cardboard, there is a deterioration of the color characteristics based on the CIE Lab system (Fig. 5). The plots of color coverage (Fig. 6) confirm the suitability of some samples of corrugated cardboard, S1–S5, S11, S15, and 16 (Table 1), for quality color reproduction.

Other samples of corrugated cardboard, S6 and S17, have average color reproduction quality.

Table 3

Correlation matrix of the studied characteristics (x_i) of corrugated cardboard and quality indicators (y_i) of inkjet printsing

No.	x_1, (surface lightness of corrugated board)	x_2, (structure type of corrugated board, the number of layers)	x_3, (corrugated board height)	y_1, (printing contrast)	y_2, (color distortion)	y_3, (color coverage)
x_1, (surface lightness of corrugated board)	1	0.1930	0.0976	0.0375	–0.6716	0.9088
x_2, (structure type of the cardboard, the number of layers)	0.1930	1	0.6272	–0.3641	–0.2300	0.3416
x_3, (height of the cardboard)	0.0976	0.6272	1	–0.0626	–0.1307	0.0737
y_1, (printing contrast)	0.0375	–0.3641	–0.0626	1	–0.0423	0.1680
y_2, (color distortion)	–0.6716	–0.2300	–0.1307	–0.0423	1	–0.6432
y_3, (color coverage)	0.9088	0.3416	0.0737	0.1680	–0.6432	1

Table 4

Values of Student's *t*-criteria of the studied characteristics (x_i) of corrugated cardboard and quality indicators (y_j) of inkjet printing

No.	x_1, (surface lightness of corrugated board)	x_2, (structure type of corrugated board, the number of layers)	x_3, (corrugated board height)	y_1, (printing contrast)	y_2, (color distortion)	y_3, (color coverage)
x_1, (surface lightness of corrugated board)	1	–3.5757	2.5739	–3.0604	–0.7872	8.7095
x_2, (structure type of corrugated board, the number of layers)	–3.5757	1	4.7673	–3.9670	–0.2623	4.4310
x_3, (corrugated board height)	2.5739	4.7673	1	2.5452	0.0404	–2.9596
y_1, (printing contrast)	–3.0604	–3.9670	**2.5452**	1	–0.1874	3.6127
y_2, (color distortion)	–0.7872	–0.2623	0.0404	–0.1874	1	–0.0016
y_3, (color coverage)	**8.7095**	**4.4310**	–2.9596	3.6127	–0.0016	1

In general, we can distinguish two groups of imprints on corrugated cardboard by the quality of color reproduction. In the first one, the level of color distortion is in the range ΔE=10...20, which exceeds the allowable norms according to the requirements of ISO 12647 [8] by 2–3 times (Fig. 5, 6). In the second – the level of color distortion is in the range ΔE=20...45 (Fig. 5, 6). The existing significant distortion in the reproduction of various shades of color can significantly reduce the suitability of the samples of corrugated cardboard, S7–S10 and S12–S14 (Table 1), for high-quality color reproduction.

The results of our study of color reproduction have made it possible to establish the influence of the main characteristics of common types of corrugated cardboard on the quality of inkjet printing based on correlation data analysis. The significant influence of the material surface characteristics on the quality of the printing process has been confirmed. Also, previous studies to determine the quality of color reproduction by inkjet printing on different types of corrugated cardboard have been supplemented.

Therefore, the selection of corrugated cardboard for inkjet printing, according to the characteristics of the surface established in this study, could ensure an acceptable level of color reproduction. In particular, one of the main indicators of the suitability of corrugated cardboard for high-quality printing may be the color characteristics of the surface of corrugated cardboard. For example, the lightness index (L^*) in the CIE Lab system, which must meet the requirements of ISO 12647 [2] and be at least L^*=80.

Limitations in the application of our research results refer to the expected dependence of the quality of color reproduction on the characteristics of the surface of corrugated cardboard, which is demonstrated by the value of color coverage of imprints according to ISO 12647, which is about G=6,000...8,000ΔE^2. Thus, these limits, obtained on the prints of some test samples, clearly indicate the acceptable quality of color reproduction in inkjet printing.

The shortcomings of this study include the use of standard settings for the inkjet printing process. To better study the possibilities of using inkjet printing on corrugated cardboard, it would be necessary, by analogy with work [16], to further study the existing modes of preparation of the layout. Further research into the quality of color reproduction on corrugated cardboard may be accompanied by the involvement of more modern and advanced inkjet printing technologies.

7. Conclusions

1. A significant influence of color characteristics of the corrugated cardboard surface (lightness index, L^*) on the quality of color reproduction has been established. In particular, greater color distortions for all shades of tone are characteristic of corrugated cardboard samples with lower surface color characteristics.

2. For the investigated imprints on corrugated cardboard, the indicator of the total contrast of printing was determined, which varied in the range K=0.25...0.50, and is within acceptable limits.

3. The overall level of color distortions (ΔE) for inkjet imprints on the studied corrugated cardboard samples was analyzed. It was found that the greater the discrepancy between the color characteristics of the corrugated board surface and the ISO 12647 standard, the greater the color distortion of inkjet imprints distortion for all shades, as well as the greater the scatter of color distortion values.

4. The color coverage of most studied imprints of corrugated cardboard corresponds to the indicators of the reference imprint. The quantitative estimation of the color coverage by the CIE Lab coordinates confirmed the results of the color reproduction analysis and revealed samples with insufficient color coverage, reduced by two times.

5. In this study, to determine the quality of color reproduction by inkjet printing on different types of corrugated cardboard, the color characteristics of the surface of different samples were analyzed. In particular, the value of the difference in the shade of white tone on the surface of corrugated cardboard, compared with the reference values of ISO 12647. Completely compliant with the standard was sample No. 11 (S11), which corresponded to corrugated cardboard and was directly intended for surface printing. All other samples had differences in the shade of white.

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