Kaunas University of Technology
Institute of Environmental Engineering
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Influence of Inks, Coatings, and Varnishes on Paper Re-Pulpability and the Environmental Performance of the Material

Master's Final Degree Project

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Sustainable Management and Production (6213EX001)

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Summary

Packaging is defined as the enclosement and protection of products for their distribution, storage, sale, consumption, and use [1], with the preferred material being paper and cardboard-based packages. Taking this into consideration, by 2021 the global paper industry reported a market value of 372.34 billion USD [2] and a production volume of approximately 417.3 million metric tonnes [3]. Therefore, when assessing global waste composition trends, it is not surprising to find that the most prominent stream after organic waste corresponds to paper and cardboard with a 17% representation [4].

Considering the above as well as the Sustainable Development Goals (SDG) tackling sustainable consumption and production patterns (Goal 12), the necessity to take urgent action to combat climate change and its impacts (Goal 13), and sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss (Goal 15), the following research had as its main objective to measure the impact of commonly used inks, coatings, varnishes, and decorations in paper and cardboard packaging repulpability according to the American Fibre Box Association (FBA) repulpability standard.

Ten (10) samples employing digital printing – 2 samples – Offset printing in cardboard packages – 5 samples – and Offset printing in paper labels – 3 samples – were sourced from Kaunas University of Technology Publishing House and packaging manufacturer Trustpack, Lithuania. Results show that 3 out of the 10 samples produced more than 15% of rejects, and therefore cannot be considered repulpable. Additionally, the 3 samples show the inclusion on foil paints or metallized engravings, which supports the conclusion that the addition of such materials to the packaging significantly reduce the amount of recoverable material.

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Santrauka

Pakuotė apibrėžiama kaip produktų uždengimas ir apsauga, skirta jų platinimui, laikymui, pardavimui, vartojimui ir naudojimui [1], o populiariausia medžiaga yra popierinės ir kartoninės pakuotės. Atsižvelgiant į tai, iki 2021 m. pasaulinės popieriaus pramonės rinkos vertė siekė 372.34 mlrd. dolerių [2], o gamybos apimtis - apie 417,3 mln. metrinių tonų [3]. Todėl, vertinant pasaulines atliekų sudėties tendencijas, nenuostabu, kad po organinių atliekų svarbiausią srautą atitinka popierius ir kartonas, kurių dalis sudaro 17 % [4].

Atsižvelgiant į tai, kas išdėstyta pirmiau, taip pat į Darnaus vystymosi tikslus (DVT), kuriuose sprendžiamas tvaraus vartojimo ir gamybos modelių klausimas (12 tikslas), būtinybę imtis skubių veiksmų kovojant su klimato kaita ir jos poveikiu (13 tikslas), tvariai tvarkyti miškus, kovoti su dykumėjimu, sustabdyti ir pakeisti žemės degradaciją ir sustabdyti biologinės įvairovės nykimą (15 tikslas), šio tyrimo pagrindinis tikslas buvo įvertinti dažniausiai naudojamų rašalų, dangų, lakų ir dekoracijų poveikį popieriaus ir kartono pakuočių atstūmimui pagal Amerikos pluošto dėžučių asociacijos (FBA) atstūmimo standartą.

Dešimt (10) pavyzdžių, kuriuose naudota skaitmeninė spauda - 2 pavyzdžiai, ofsetinė spauda kartoninėse pakuotėse - 5 pavyzdžiai ir ofsetinė spauda popierinėse etiketėse - 3 pavyzdžiai, buvo gauti iš Kauno technologijos universiteto leidyklos ir pakuočių gamintojo Trustpack, Lietuva. Rezultatai rodo, kad 3 iš 10 pavyzdžių buvo gauta daugiau kaip 15 % broko, todėl jų negalima laikyti atpažįstamais. Be to, šiuose 3 mėginiuose matyti, kad į pakuotę įtraukta ant folijos dažų arba metalizuotų graviūrų, o tai patvirtina išvadą, kad tokių medžiagų įtraukimas į pakuotę gerokai sumažina atgautinos medžiagos kiekį.

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List of abbreviations and terms

CEPI	Confederation of European Paper Industries
EB	Electron Beam
ERIC	Effective Residual Ink Concentration
EU	European Union
FBA	Fibre Box Association
FCM	Food Contact Materials
FCT	Flat Crush Test
GWP	Global Warming Potential
ISO	International Organization for Standardization
ISO 14040:2006	ISO Standard for Life Cycle Assessment
LCA	Life Cycle Assessment
MOB	Mineral Oil-Based inks
PBS	Polybutylene succinate
PCL	Polycaprolactone
PGA	Polyglycolic Acid
PHA	Polyhydroxy Alkenoates
PLA	Polylactic Acid
PPW	Packaging and packaging waste
PU	Polyurethane
PVOH	polyvinyl alcohol
SDG	Sustainable Development Goals
SOB	Soy Oil-Based inks
UV	Ultraviolet
VOC	Volatile Organic Compounds

Introduction

The following research aims to determine the impact of printing inks and coatings on the repulpability of paper fibres used for the manufacturing of recycled packaging materials in different consumer industries. With this in mind, 10 samples of paper and cardboard packaging of consumer goods were subjected to the repulpability test and compared against a control sample of 280g not printed and uncoated paper to assess the impact of the different printing technologies, inks, coatings, and varnishes on the repulpability of the material. **Table 1** details the characteristics of each sample along with the printing technology used for its manufacturing, as well as a brief description of paints and varnishes, and if any additions and/or decorations are present in the finished product:

Table 1. Selected samples

CONTROL SAMPLE				
No.	**Grammage**	**Coating & printed**	**Additions/decorations**	**Coating**
1.	280	Not coated Not printed	-	no
DIGITAL PRINTING				
No.	**Grammage**	**Coating & printed**	**Additions/decorations**	**Coating**
1.	280	Not coated Printed	-	No
2.	280	Coated Printed	-	Polyurethane (PU)
CARDBOARD PACKAGES – OFFSET PRINTING				
No.	**Package ID**	**Carton grammage (g)**	**Description of paints and varnishes**	**Additions/decorations**
1.	UV paint & UV varnish	300	UV paint and UV varnish	Gold foil
2.	UV paint & dispersion varnish	260	UV paint and dispersion varnish	-
3.	UV paint & UV varnish	400	UV paint and UV varnish	-
4.	Simple paint & dispersion varnish	250	Simple paint and dispersion varnish	-
5.	UV paint & dispersion varnish	300	UV paint and dispersion varnish	Metallised engraving
PAPER LABELS - OFFSET PRINTING				
No.	**Package ID**	**Carton grammage (g)**	**Description of paints and varnishes**	**Additions/decorations**
1.	Plain label	70	Plain label Simple paint without varnish	-

2.	Metallised label	68	Metallised label Foil paints without varnish	-
3.	Plain label with gold foil	70	Plain label Simple paint without varnish	Gold foil

Out of the ten (10) assessed samples, three yielded a percentage of rejects above 15%, which according to the American Fibre Box Association repulpability test classifies the packaging as not repulpable. Out of these three samples, two are paper labels using the offset printing method, with either foil paint or gold foil included in the specifications, while the remaining sample corresponds to cardboard packaging with offset printing on 300 grammage cardboard, UV paint, dispersion varnish and a metallised engraving. These results, although not definitive do show that the inclusion of such additions can have significant impact on the repulpability, recyclability, and circularity of a package.

1. Objectives

1.1. General objective

Determine the impact of printing inks, coatings, and varnishes on the repulpability and recyclability of paper fibres used for the manufacturing of packaging used within the consumer goods industry.

1.2. Specific objectives

1. To perform an analysis of printing methods and printing technologies used in packaging production processes.
2. Investigate legal requirements and legal regulations limiting the use of printing inks and technologies in packaging production.
3. To analyse the specifics of the application of paper packaging de-pulping technologies, and to review the repulpability research methods used in the world.
4. To review the results of scientific research and published publications on Impact of inks, coatings, and printing technologies on paper recyclability.
5. Apply the voluntary standard for repulpability test according to the Fibre Box Association Method to measure the rate of repulpability of the assessed materials.
6. Based on the results of the conducted research, to present conclusions and recommendations regarding the application of different printing methods in the production of packaging and their influence on paper washing and, at the same time, on the negative impact on the environment.

2. State of the art on fibre recovery and quality

Packaging is defined as the enclosement and protection of products for their distribution, storage, sale, consumption, and use [1]. According to Fernández [5] global demand for packaging in 2019 was distributed between six (6) main materials, including paper and cardboards with a 33.2% participation, flexible plastics making up 25.5% of demand, rigid plastics representing 18.7%, metal, glass and other packaging materials, representing 12.1%, 5.8% and 4.7% respectively; making paper and cardboard the leading packaging material worldwide.

In 2021 the global pulp and paper industry reported a market value of 372.34 billion USD [2] and a production volume of approximately 417.3 million metric tonnes [3], equal to a 4% increase in production compared to 2020. According to CEPI [6], paper and board production is most prominent in Asian countries, representing up to 47.3% of supply, followed by Confederation of European Paper Industries (CEPI[1]) countries with 21.4%, and 19.2% in North America, while demand follows a similar pattern, with the most prevalent occurring in Asia, with a 49.2%, and CEPI countries and North America reported a demand of 17.7% [6].

The process of Paper-based packaging production starts with the manufacturing of pulp and paper, which sources raw materials like pine, eucalyptus, and recycled fibres to be sent to the de-barking and chipping stage, in the case of virgin fibres, where the wood is stripped of its bark and reduced to smaller chips. The resulting woodchips and bagasse are then sent to pulping, where they can be either treated through chemical or mechanical pulping. The first consists of cooking the woodchips to remove any trace of lignin, whereas the second grounds the input material to separate the fibres [7].

At the same time, recycled paper is re-introduced into the process in the pulping stage, where it is dissolved into pulp to separate the component fibres that the go into the de-inking process, to remove any adhesives, ink and other contaminants present [8]. By this point, both the virgin and recycled fibres are sent to the cleaning stage of the process, where they are washed, screened, and dried to be sent to the headbox, where the existing mixture of fibre and water is squirted through a horizontal slit, partially dried, and then headed to the wire section [7]. During this next stage of the process, the afore mentioned mixture is further spread and consolidated into a thin mat or sheet [7].

Finally, at the press section, half of the remaining water content is removed, and the produced sheet goes into the drying stage, where it goes through a series of cast-iron cylinders that dry the sheet. By this point of the process, the paper is already at a state to be used and sold, however further steps of production include the coating process, where colour is spread onto the paper surface multiple times in order to produce high quality printing and packaging paper; the calendering phase where the produced sheet is subjected to high temperatures to achieve smooth and glossy properties; and lastly the finishing process, where the paper is cut into sheets for printing, converting, commercialization, and distribution [7]. The overall process as described by [7] is shown in **Figure 1**:

[1] Members of CEPI in 2021: Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, The Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom.

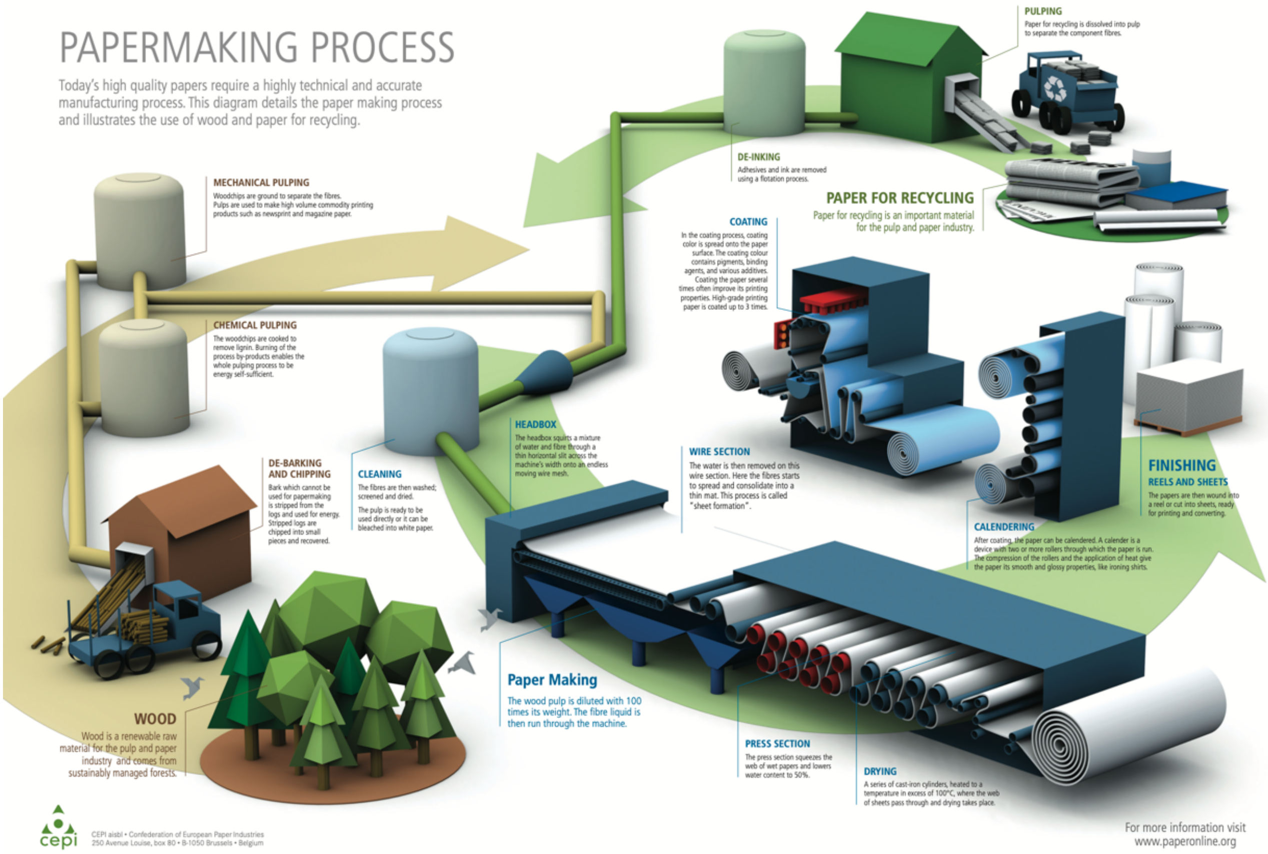

Figure 1. Papermaking process [7]

Papers used for packaging usually fall into the category of coarse paper, made out of unbleached kraft softwood pulp that include waxed paper, characterized by having a barrier against liquids and vapours, vegetable parchment, glassine paper, greaseproof paper, bleached paper, and kraft paper [9].

2.1. Printing technologies

The selection of a printing method and its applicability to paper packaging is very much reliant on a number of related factors and parameters, not only because of the ink properties, but also on the level of accuracy and resolution of the printed product, the uniformity, wetting control and interface formation, the desired quality of the finished product, along with the added costs of production [10]. Some of the more traditional printing technologies available and highly utilized in industrial settings include the following methods [10]:

Flexography printing is mostly used in the printing of **food flexible packaging**, this method uses a flexible rubber plate or letterpress to print on the substrate. The small wells holding the ink rotate in tandem with an impression cylinder, through which the paper board passes effectively printing the desired patterns onto the material, and then moving on to a UV ray device for curing. Inks used for this specific method can be either synthetic or natural resins dissolved in boiling solvents [10].

Rotogravure printing method is mostly applied for **flexible food packaging**, where small cavities engrained in the printing cylinder engrave the pattern into the substrate as it is rolled through. The brightness and intensity of the printed product depends on the depth of the cells, and the number of colours to be used determine the number of printing units necessary fort its production, so the printing process takes both into consideration during the design process. Once the substrate has passed through the impression roller and engraved cylinder it is sent to a drying unit before moving to the next colour unit. Gravure inks are characterised by utilising organic solvents including esters and alcohols with low boiling points that minimise migration from the substrate to the packaged product, however the use of water-based inks is also possible [10].

In inkjet printing the use of a noncontact dot matrix is the most defining characteristic of this printing method. Ink droplets are jetted from small nozzles onto the substrate medium to create the desired effect, although this technology is further divided into thermal and piezoelectric mechanisms as well as continuous inkjet. The main idea behind this method is to break the ink into small droplets electrically charged that continue on to be applied into the substrate, while the droplets not charged are recirculated. The most common use of this printing method **includes display applications**, but special interest on UV-continuous inkjet printing for polymeric food packaging has been on the rise due to its image quality, durability, speed, and curing [10].

In offset printing, the surface with and without printed image lies on the same plane, the area without an image is meant to be hydrophilic and therefore is wetted with a mixture of water and alcohol, while the area where the image is meant to be printed is hydrophobic and has to be wetted with oil. The type of inks used for this method require high viscosity and temperatures between 25 º and 40 ºC, while resins should be soluble in the used solvent to stabilise it and be ensure proper drying of the image. On the other hand, solvents used for offset printing include vegetable oils, mineral oils, and fatty acid esters. The latter being predominantly used for printing food packaging due to the low levels of migration [10].

An analysis of available printing technologies applicable to paper-based packaging has shown a wide array of possibilities within the industry. For example, [11] presents the three (3) main technologies and research areas available in the field of digital printing, stating that the use of this methods allows higher printing efficiency by simplifying the overall process, with some cases showing a production of up to 8000 sheets/h of A4 paper, permitting a high rate of personalization capabilities and supporting most file formats to meet customer needs more accurately than other traditional printing methods.

Electrostatic imaging digital printing allows the generation of electrostatic latent images based on light conductors and laser scanning technologies. Through the use of this technology, small particles of ink adhere to the surface of the package forming the required image or pattern [11]. On the other hand, **inkjet imaging** uses ink droplets to form an image and generate various colours of ink in accordance with the design requirements as previously described, while **magnetic imaging** makes use of arranged magnetons to create the image [11]. Other technologies include **nanoimprinted lithography and injection mould coatings, and extrusion and lamination coatings,** making use of two different polymer pellets to create a multilayer web of plastic film [10].

2.2. Types of inks and coatings

As stated above, the efficiency of any of the explained deinking methods is highly reliant on the type of ink as well as the printing method used. In short, inks are made up of pigments providing the visible colour, while resins provide the level of gloss, adhesion, absorption, flexibility, and hardness [12]. Additionally, inks require the addition of solvents that allow the fluidity required by printing technologies, which can then be evaporated or absorbed by the packaging depending on the type of ink used [13].

According to Osman [12] and Shujie et al. [14] some of the most widely used inks include:

- Mineral Oil-Based (MOB) which is produced from petroleum-based minerals, these inks contain higher amounts of Volatile Organic Compounds (VOC) like toluene, benzene, and xylene, therefore posing greater harm to human health and the environment.
- Vegetable Oil or Soy Oil-Based (SOB) is the oil obtained from soybeans is refined and mixed with other compounds including natural waxes and resins. It is mainly used in the printing of newspapers and other mass media documents and has become increasingly attractive due to its cost-effectiveness, the low levels of VOCs present and the easiness of removal during the deinking process.
- UV Cured (UV) is a type of ink characterized by the need to dry the ink during the application phase through the use of UV lights, as well as their resistance to water.
- Lithographic inks: or offset oil-based inks, using water resistant vehicles and pigments that cannot dissolve in water and/or alcohol, and a 40% concentration of vegetable oil and 20% of mineral oils. In this case, the drying process can be done either by i) quick absorption of the ink into the fibre and ii) physical drying through the exposure of the surface to 60 ºC temperatures. The last method being applied to inks with a 35-45% mineral oil composition.

Considering the poor barrier properties inherent to uncoated paper, it is unsuitable as primary packaging material, therefore, coatings are applied with the aim of improving its resistance against water vapor permeability, oxygen permeability, mineral oils diffusion, and transfer of greases, among other factors [15].

In paper packaging, coating formulations are manufactured using mineral pigments to enhance optical properties, binders for adhesion and strength properties of the pigment and coating layers, polymeric thickeners to adjust the runnability and stabilise the substrates' printing properties, as well as pH controllers, dispersants, dyes, and other additives to improve paper properties including air permeability and tear resistance [16]. For example, polyurethane (PU) coating is a petroleum based polymer regarded as one of the most important and versatile coating materials due to the wide array of applications in different industries [17], in the packaging industry it provides products with an increased printing strength, high gloss, elasticity, good pigment compatibility, and in some cases resistance to hydrocarbon solvents.

Some coatings technologies used in the paper-based packaging industry as detailed by [1] include:

- Abrasive coatings: applied through the use of screen-printing technologies by pressing the coating mineral against the paperboard and held by applying a layer of adhesive bond.
- Drip-off coating: this application method creates a matt- gloss effect through the use of a photopolymer plate along with specially formulated oil-based overprint varnishes and water-based high gloss coatings. It is worth mentioning that this method is specific to paper, board, and label paper substrates because of its absorption properties.
- Spot UV coating: this type of coating that uses polymer resins and ultraviolet light to add a protective layer on specific areas of the design. This coating method is applicable to many types of substrates including paper, plastics, and metals.

Additionally, research on bio-based materials for barrier coating applicable to paper packaging has gained traction, bringing to attention the use of sustainable coating materials such as polylactic acid (PLA), polyhydroxy alkenoates (PHA), starch, alpha 1,3 glucan, and rubber latex coatings among many more [15]. Some of the more prominent characteristics of the listed biomaterials are listed below:

- PLA is derived from lactic acid, PLA is biodegradable through the implementation of hydrolysis and microbes. Its most attractive qualities include low cost of production, high availability of raw materials, as well as low energy consumption throughout the production process [15]. However, PLA has shown poor resistance to oxygen and water permeability due to its amorphous nature, requiring its improvement through crystallisation.
- Polyglycolic acid (PGA), which has shown excellent barrier properties in terms of gas permeability and mechanical strength. Chemically speaking, the structure of PGA is similar to that of PLA, making it an appropriate choice for packaging coatings [15].
- Poly hydroxy alkenoates (PHA) has shown high potential in replacing petroleum-based coatings for paper packaging, providing good oxygen and water vapour permeability. However once exposed to physical aging at room temperature can have negative effects on the packaging integrity [15].
- Polybutylene succinate (PBS) are most attractive for food packaging applications, PBS has shown good values in terms of oxygen and water vapour permeability, its one drawback being higher cost of production when compared to petrol-based coatings [15].
- Starch is a naturally available polymer which requires physical, chemical, and enzymatic modifications to provide the necessary mechanical and flexibility properties to act as an adequate coating for paper packaging. One of the most used modifications include the addition of polyvinyl alcohol (PVOH) to achieve an excellent barrier against moisture and oil [15].
- Cellulose is one of the primary raw materials in the paper production industry, cellulose derivates can be used in the production of coating materials. Further research on the subject has shown that although widely available, cellulose has negative properties including water insolubility, high crystallinity, and a poor ability to form uniform films [15].
- Chitosan, a naturally available polysaccharide biocompatible, with biologically degradable properties that has shown promising barrier properties such as water, vapor, and oxygen permeability [15].

2.3. Impact of inks, coatings, and printing technologies on paper recyclability

A number of cases where the impact of inks, printing methods, and applied coatings and varnishes on the recyclability, deinking and repulping of paper-based packaging have been conducted. For example, [18] selected offset-printed paper-based packaging used for pharmaceutical products, to explore the influence of moisture and temperature on the mechanical properties and recyclability potential of the material by exposing it to accelerated ageing in controlled conditions of 40% humidity at 60 ºC for three (3), six (6), and nine (9) days.

The resulting samples were then subjected to a Flat Crush Test (FCT), where a sample of board is subjected to increasing force, applied perpendicular to the surface of the board [19]. The results of this test showed that bending strength of the packaging is directly proportional to the aging time, meaning that the non-aged boxes required more force than the aged packaging under the previously stated laboratory conditions, proving that exposure to temperature and humidity can have a slight impact on the resistance as well as other mechanical properties of the pharmaceutical packaging [18].

The second stage of testing required the comparison between aged and non-aged packaging by performing the INGEDE Method 11 – Assessment of print product recyclability: Deinkability test, where the samples were disintegrated and sent to a flotation cell [18]. The obtained pulp allowed the creation of laboratory hand sheets of $45 g/m^2$ from deinked and undeinked pulp to implement the deinkability evaluation according to the hand sheets optical properties and the residual ink area, making use of the image analysis method and comparing the result to the ISO 2470: Brightness, ISO 11475: Whiteness and colour components, and ISO 2471: Opacity [18].

Vukoje et al.[18] conclude that elevated humidity and temperature slightly affect the separation of printed ink from the substrate, which in turn resulted in recycled fibres with different optical properties where brightness according to the ISO 2470 decrease proportionally to the aging time. Additionally, according to the results obtained through the deinkability test, the largest amount of removed ink particles was found in the non-aged samples, while tests for brightness and CIE whiteness is lower in laboratory sheets from recycled boxes, resulting in a reduced quality of the optical and mechanical properties of recycled fibres [18].

Another example of research in the field of packaging recyclability is found in Green [20], where the development of transfer coatings meant to replace film products, the optimisation of robust and durable packaging along with the recyclability of transferred coatings on paperboard is discussed. In terms of flexibility, an in-house creasing test was applied with a thickness of 12 μm which was the cured with a mercury arc lamp, laminated to paperboard, folded and placed in a hydraulic press, unfolded, flattened, and creased until the transfer coating cracked and the paperboard fibres were exposed [20].

Printability was assessed through the crosshatch test where the formulations were applied to the carrier film with a thickness of 12 μm, cured using a mercury arc lam and laminated [20]. Finally, a standard UV flexographic printing ink was applied to the laminated transfer coating and sent to the crosshatch test [20]. Once all other stages of testing were completed, the finished samples were tested for repulpability and recyclability according to the Western Michigan University SBS Equivalency (WMU SBS-E) testing protocol [20].

Results of the research in terms of the last stage of testing are as follows; the repulpability of laminated and printed fibreboard measured the fibre yield of the material after repulping, should the sample produce more than 80% of recovered fibres, the material is deemed as repulpable, which then allows the recovered fibre to be sent for recyclability testing to determine if the fibre shows conditions fit to be used in recycled feedstock based on the mechanical and visual properties of paper made from recycled materials [20]. The obtained results showed that laminated decorative coating was successfully removed from the substrate and more than 80% of the initial fibres were easily recovered, while the mechanical and optical properties of the material show very slight differences to the control material, permitting the reuse of decorated paperboard in the manufacturing of packaging [20].

A third case study where the efficiency of impurity separation form cellulose pulps obtained from pharmaceutical laminated cardboard packaging used standard samples to first, determine the efficiency of the deinking process on i) cardboard printed substrate (S), and ii) pharmaceutical laminated cardboard packaging (P) applying a UV offset printing method, and varnished with a UV-cured varnish [21].

The samples were turned into cellulose following the process established through the ISO 5263-2:2004 standard, while the separation of impurity particles was performed following the INGEDE Method 11 to compare against as a test framework, while laboratory-obtained paper sheets were subjected to a method of deinking without the use of chemicals, and a combination method created from the INGEDE Method 11 and the non-chemical utilisation method [21]. The research goes further in evaluating optical characteristics of the paper hand sheets including the diffuse blue reflectance factor (ISO 2471-1:2016), the effective residual ink concentration (ERIC) according to the ISO 22754:2008, and the colour determination of paper and board (ISO 5631-3:2015) [21].

The brightness measurement of the samples from printed boxes against printed media showed an increase in values after the separation of impurity particles, additionally the highest values for brightness were obtained through the application of the INGEDE Method 11 for recycling paper and board [21]. In terms of the colorimetric coefficient L^*, which shows the influence of the reflection of colour as a combination of tint, saturation and dark/light value, results confirm the brightness test results [21].

[21] conclude that the three compared methods successfully remove impurity particles from pulp used for laminated boxes for pharmaceutical packaging, however it is worth noting that the presence of adhesives and silver foil for lamination presented a challenge in the removal; this resulted in a higher concentration of adhesives in the pulp, which in turn agglomerated. Overall, the study demonstrated the possibility of employing a non-chemical procedure for the separation of impurity particles from paper and pulp, thus increasing the environmental sustainability of the process as a whole [21].

2.4. Legal and regulatory requirements

Following the supply and demand of paper and paper-based products, the end-of-life stage shows that packaging and packaging waste (PPW) can make up to 49% of the total mass of a PPW sample [22]. Furthermore, paper and paper-based packaging is widely used for food packaging, therefore requiring the incorporation of additional materials like printing inks, phthalates, surfactants, bleaching agents, and hydrocarbons bearing in mind relevant factors such as heat saleability, printability, strength, barrier properties, legal requirements among many more [23].

Some of the aforementioned legal requirements applicable to paper-based packaging in the European Union (EU) include:

Directive 89/109/EEC – On the approximation of the laws of the Member States relating to materials and articles intended to come into contact with foodstuffs, including water. This Directive states that all materials and articles shall be manufactured in compliance with good manufacturing practices so under normal circumstances or conditions, they do not transfer their constituents to foodstuffs in quantities that may endanger human health, bring an unacceptable change in the composition of the foodstuff or a deterioration in the organoleptic characteristics thereof [24].

Furthermore, it establishes a list of materials and articles to be covered by specific Directives, which include varnishes and coatings, regenerated cellulose, paper, and board, among others. The Directive also specifies the health criteria to be applied in the drafting of said specific Directives, allowing the establishment of materials and articles intended to come into contact with foods and foodstuffs according to their liability to migrate and the toxicity of the substance [24].

Directive 94/62/EC – The directive aims to harmonise measures concerning the management of packaging waste in order to prevent any impact thereof on the environment of all Member States. For this, the Directive lays down measures for the prevention of packaging waste generation, the reuse of packaging, recycling, and other forms of recovery to reduce the final disposal of this type of waste [25].

Regulation (EC) No. 1935/2004 – This regulation provides a harmonised legal framework on general safety principles and inertness for all Food Contact Materials (FCMs). The applicable principles require that materials do not:

- Release their constituents into food at levels harmful to human health.
- Change food composition, taste, and odour in an unacceptable way.

At the same time, the framework:

- Provides special rules on active and intelligent materials (they are by their design not inert)
- Powers to enact additional EU measures for specific materials.
- Provides a procedure to perform safety assessments of substances used to manufacture FCMs involving the European Food Safety Authority.
- Sets rules on labelling, including indicators for use.
- Requirements on compliance documentation and traceability.

Regulation (EU) No. 10/2011 – On plastic materials and articles intended to come into contact with food, including the following [26]:

- Materials and articles and parts thereof consisting exclusively of plastics.
- Plastic multi-layer materials and articles held together by adhesives or by other means.
- Materials and articles that are printed and/or covered by a coating.
- Plastic layers or plastic coatings, forming gaskets in caps and closures that together with those caps and closures compose a set of two or more layers of different types of materials.
- Plastic layers in multi-material, multi-layer, and articles.

2.5. Repulpability process and testing

Repulpability is defined as the ability of paper packaging to undergo the processes of re-wetting and fibre separation with the aim of manufacturing new packaging materials from the obtained fibre yield [27]. Because of this, several laboratory procedures and testing methods have been developed withing the pulp, paper and packaging industries, with the Fibre Box Association (FBA) Voluntary Protocol and the CEPI recyclability laboratory test method being the most widely accepted standards in the industry, the first one being used for the development of this research and described in more detailed in section **3.1 Voluntary standard for repulpability and recyclability**.

As stated by the Sustainable Packaging Coalition [27], the goal of recyclability testing aims to predict if a package can be converted into usable fibre through the use of paper mills procedures without causing operational problems, while also proving beneficial to the betterment and enhancement of recycling supply chains, as well as provide informed results in terms of the choice of processes, materials and composition in the design stages [27].

According to the testing methods previously mentioned, the two most important steps to recycling testing rely on the laboratory method and the established thresholds for concluding whether the fibre can be considered recyclable or not [27]. Additionally, it is worth mentioning that most of the developed repulpability and recyclability methods consist of at least four (4) main stages that include: i) the preparation of samples; ii) the repulping of samples; iii) screening, which can be done through coarse and fine screens; and iv) analysis of results.

The process then allows the analysis of several indicators related to fibre and paper quality such as fibre separation, visual appearance of formed sheets, number of rejects form the screening stage, amount of recovered disruptive materials (i.e., adhesives, metals, plastic film, etc), and strength [27]. In general, the afore mentioned stages for laboratory testing are described as follows:

Step I – Sample preparation: The selected sample must be representative of the product for which the test is being carried out and should be compared against a control sample already deemed as recyclable. To be representative, the sample must be sufficient to perform all the necessary measurements and to be subjected to all the procedures described within the testing protocol. Often samples are prepared through size reduction methods such as cutting and/or shredding [27].

Step II – Pulping: During this stage, the sample is mixed with water, causing the fibres to separate through suspension, which then allows the collection of any non-fibre material or rejects separately from the recovered fibres. For this step to be successful, the sample must be subjected to specific conditions such as temperature, pH, and consistency, according to the directions of the equipment used [27]. In some testing methods, the recovered fibres are converted into paper sheets to be used in further analysis [27].

Step III –screening: As stated above, screening can be done in two (2) stages, the first one being coarse screening, where the aim is to remove any impurities from the repulped fibres as well as any chunks of not properly pulped sample. These are then weighed and accounted for as “coarse rejects”, which is considered as one of the principal indicators of paper repulpability and is often reported as a percentage of the mass of the sample. While the threshold can vary from method to methos, it is commonly understood that the yielded rejects must not be above 20% of the weight of the sample for the material to be considered as repulpable [27].

On the other hand, the second screening stage is known as “fine screening” where the pulp obtained from the coarse screening is passed through a second screen with smaller slots to further remove any impurities and or contaminants. Some variables to consider in this stage include temperature, pH, slot size, slurry agitation, and screening time. The recovered fibres are then shaped into hand sheets to be tested for mass of rejects, stickies, strengths, and visual homogeneity of hand sheets [27].

Step IV – Analysis of hand sheets and test report: After all the previously explained steps have been fulfilled, test results must be collected and analysed, some of the most widely accepted reports include the following structure, however changes can be done according to the applied testing procedure:

– Reference to the applied testing standard.

- Identification of equipment used.
- Description of the paper-based material.
- Type of software / equipment used for image analysis.
- Photographic documentation.
- Results of test according to specification, which can include:
- Flakes, residues, and adhesive present.
    - Dissolved and colloidal solids (%).
    - Pass/ fail of the test.
- Name and signature of the test lab, responsible manager, and date of the test.
- Ash content.
- Fibre yields as well as accepts and/or rejects.
- Hand sheet formation.

3. Research Methods for the impact of paper

3.1. Voluntary standard for repulpability and recyclability

The voluntary standard for repulping paper and board treated to improve its performance in the presence of water and water vapor, modified by the *Voluntary standard for repulping and recycling corrugated fibreboard treated to improve its performance in the presence of water and water vapor* method [28], was employed for the development of this research. Its purpose is to establish a repeatable method for stimulating a commonly used subset of recycling process [28].

The test determines the repulpability of treated paper and board by determining the fibre-on fibre yield, when the treated material is processed according to the proposed methodology. The obtained samples must then be subjected through three (3) tests, passing two (2) out of three (3). In most cases however it is enough to perform two tests to determine the repulpability of the material. The following subsections describe the laboratory equipment along with the test procedure.

3.1.1. Equipment

The equipment and materials necessary to perform the repulpability test includes: i) specimen cutting device; ii) a balance with an accuracy of 0.01; iii) a waring blender; iv) hot water at a temperature of 52 ºC ± 5° C; v) a British disintegrator; vi) an open flat screen 10 cut (0.010”); vii) aluminium weighing pans; and viii) a laboratory oven heated at 105 ºC. The following images show the listed equipment.

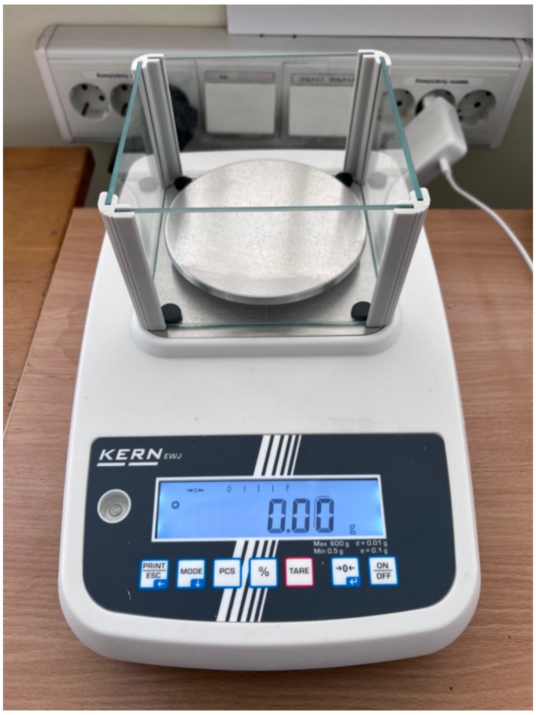

Figure 2. Balance - accuracy of 0.01g

Figure 3. Waring blender

Figure 4. British disintegrator

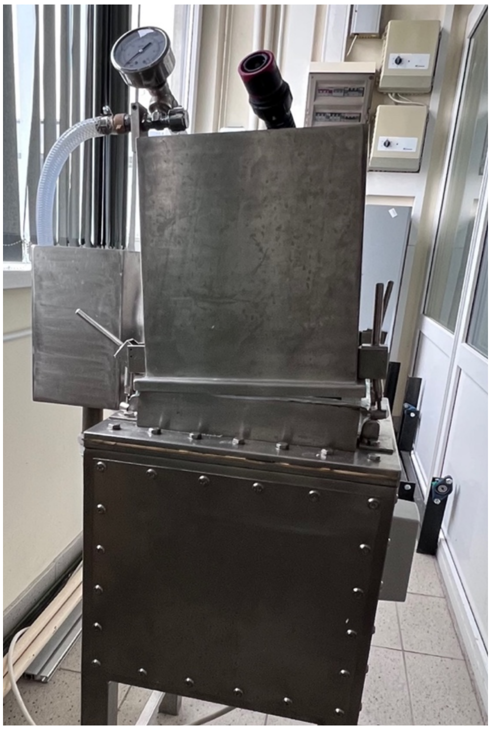

Figure 5. Somerville screens

Figure 6. Aluminium weighing pans (2.57 g ± 0.02)

Figure 7. Laboratory oven (105ºC)

3.1.2. Test procedure

To start the repulpability test, the laboratory oven was heated at 105 ºC for an approximate of 24 hours in order to have it ready to store the samples after gathering the rejects. The second step consisted of cutting the sample materials into strips of approximately 31.8 mm by 102 mm until achieving a total weigh of 26.75 g per sampled material, which were then placed into 1500 ml of water heated at 52 ºC ± 3 °C. Once soaked, the samples were moved to the waring blender and set at a speed of 15,000 rpm for four (4) minutes [28].

After blending, the samples were moved from the blender into the British disintegrator, all fibres left in the blender were rinsed with 500 ml of water at 52 ºC ± 3° C and deflaked for five (5) minutes at 3000 rpm. The resulting mixture was moved to the open Somerville screens with 0.254 mm slots, maintaining a 1" water head for twenty (20) minutes, after which the residue was collected in aluminium weighing plates and placed in the laboratory oven for 12 hours at 105 ºC. The resulting sample was once again weighed to calculate the net rejects [28]. An overview of the process is illustrated in the following diagram:

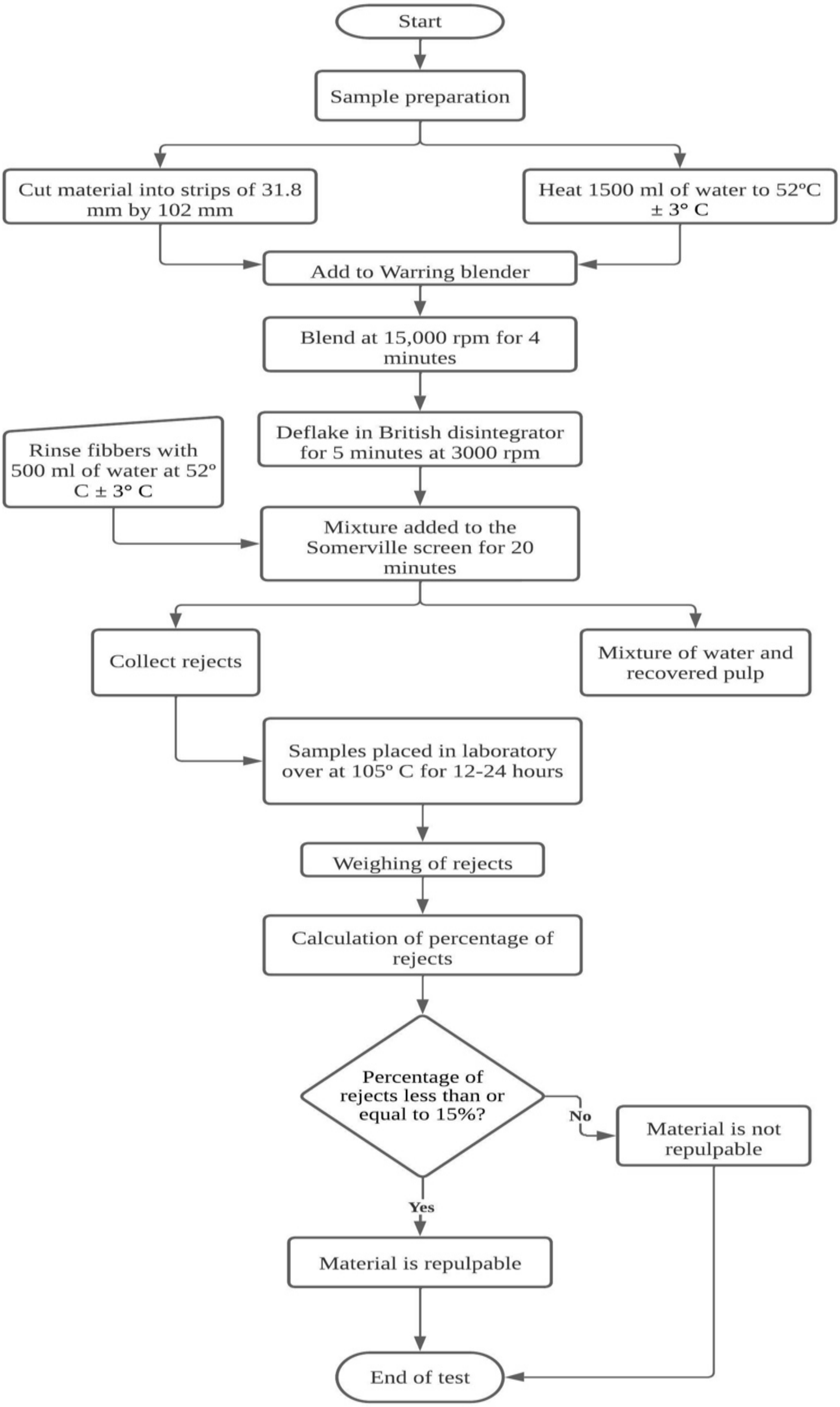

Figure 8. Repulpability test procedure [28]

Table 2, **Table 3**, **Table 4**, and **Table 5** describe the characteristics of each selected sample according to its printing method, grammage, applied coating and/or varnish, as well as any additions or decorations to the material.

Table 2. Control sample - characterisation

CONTROL SAMPLE				
No.	**Grammage**	**Coating & printed**	**Additions/decorations**	**Coating**
1.	280	Not coated Not printed	-	no

Figure 9. Control sample

Table 3. Characterisation of digital printing samples

DIGITAL PRINTING				
No.	**Grammage**	**Coating & printed**	**Additions/decorations**	**Coating**
1.	280	Not coated Printed	-	No
2.	280	Coated Printed	-	Polyurethane (PU)

1. Printed and uncoated
2. Printed and coated

Figure 10. Digital printing samples 1 & 2

Table 4. Characterisation of offset printing samples - Cardboard packages

CARDBOARD PACKAGES - OFFSET PRINTING				
No.	**Package ID**	**Carton grammage (g)**	**Description of paints and varnishes**	**Additions/decorations**
1.	UV paint & UV varnish	300	UV paint and UV varnish	Gold foil
2.	UV paint & dispersion varnish	260	UV paint and dispersion varnish	-
3.	UV paint & UV varnish	400	UV paint and UV varnish	-
4.	Simple paint & dispersion varnish	250	Simple paint and dispersion varnish	-
5.	UV paint & dispersion varnish	300	UV paint and dispersion varnish	Metallised engraving

1. UV paint & varnish

2. UV paint and dispersion varnish

Figure 11. Offset printing samples – cardboard packaging (i)

3. UV paint and UV varnish

4. Simple paint and dispersion varnish

5. UV paint and dispersion varnish

Figure 12. Offset printing samples – cardboard packaging (ii)

Table 5. Characterisation of offset printing samples - Paper labels

PAPER LABELS - OFFSET PRINTING				
No.	**Package ID**	**Carton grammage (g)**	**Description of paints and varnishes**	**Additions/decorations**
1.	Plain label	70	Plain label Simple paint without varnish	-
2.	Metallised label	68	Metallised label Foil paints without varnish	-
3.	Plain label with gold foil	70	Plain label Simple paint without varnish	Gold foil

1. Plain label Simple paint without varnish

2. Metalized label Foil paints without varnish

3. Plain label Simple paint without varnish

Figure 13. Offset printing samples – paper labels

3.1.3. Calculation of rejects

The calculation of rejects was performed using the following equation, while the results were reported in the tables presented on **Table 6**. For a material to be considered as repulpable, the percentage of obtained rejects should be less than or equal to 15%, rounded to the nearest 0.1% [28]:

$$\% \ of \ rejects = \frac{Net \ rejects \ (g) \times \ 100}{Total \ oven \ dry \ sample \ (g)}$$

Table 6. Test result template [28]

Results			
TEST NO.:	(Sample identifier)		
SAMPLE:			
	Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?	Yes ☐ No☐	Yes ☒ No☐	Yes ☐ No☐
FINISHED SAMPLE			
Total over dry weigh (g)			
Net "rejects" (g)			
% of "rejects"			
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☐ No☐	Yes ☐ No☐	Yes ☐ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

4. Results

4.1. Repulpability test

Table 7 shows the obtained results for each of the ten (10) selected samples as well as the control sample. A total of 20 tests were performed and compared to define if the samples pass the repulpability test or not. Further details on each printing technology, sample specifications and analysis are provided in the following subsections. Additionally, a comparison between samples and printing technologies is shown in **Figure 14**.

Table 7. Repulpability test results

SAMPLE		Test 1		Test 2	
		Net "rejects" (g)	% of "rejects"	Net "rejects" (g)	% of "rejects"
Control sample	**Clean paper**	0.01	0.04%	0.02	0.07%
Digital printing	**1. Printed and uncoated paper**	0.02	0.1%	0.52	1.9%
	2. Printed and coated paper	2.18	8.2%	2.09	7.8%
Offset printing Cardboard	**1. UV paint and UV varnish**	0.59	2.21%	0.7	2.62%
	2. UV paint and dispersion varnish	3.97	14.8%	4.00	15.0%
	3. UV paint and UV varnish	3.35	12.5%	3.20	12.0%
	4. Simple paint and dispersion varnish	0.97	3.63%	1.07	4.00%
	5. UV paint and dispersion varnish	5.21	19.5%	4.93	18.4%
Offset printing paper labels	**1. Plain label**	2.15	8%	2.45	9%
	2. Metalized label Foil paints without varnish	11.73	44%	14.04	52%
	3. Plain label Simple paint without varnish & gold foil	0	0%	0	0%

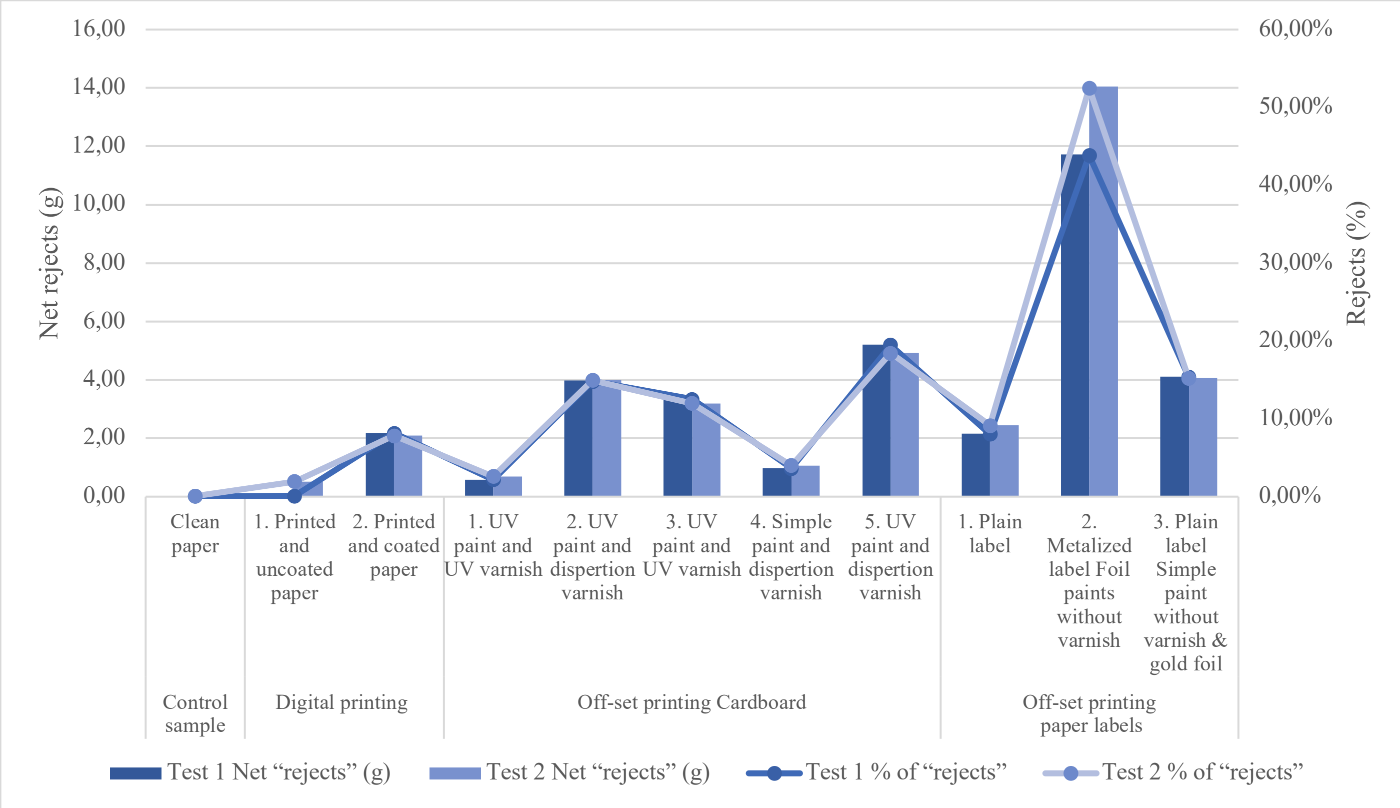

Figure 14. Repulpability test results

Once the samples completed the testing procedure described in **section 3.1.2,** the resulting rejects were taken out of the laboratory oven and weighed on a balance with a 0.01 g accuracy to determine if the packages and labels can be considered as repulpable according to the FBA [28], and compared to the control sample of 280 g paper, both uncoated and nor printed, which, as seen on **Table 8** produced 0.04% of rejects on the first test, and 0.07% and 0.04% on the second and third tests.

Table 8. Repulpability test results – Clean paper 280 g

Results			
TEST NO.:	Clean paper		
SAMPLE:	1.		
	Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☒ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net "rejects" (g)	0.01	0.02	0.01
% of "rejects"	0.04%	0.07%	0.04%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☒ No☐	Yes ☒ No☐	Yes ☒ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

4.1.1. Digital printing samples

The first sample for digital printing is made out of 280 g of paper printed with regular ink and with no added coating, resulting in 0.28 g on average of rejects, with the first test showing a 0.075% of rejected material, and tests two and three recording a 1.94% and 1.16% of rejects respectively. It is the possible to conclude that the material if fit to be repulped.

Table 9. Repulpability test results – Digital printing paper: Printed and uncoated

Results			
TEST NO.:	DP PAPER UNCOATED AND PRINTED		
SAMPLE:	1.		
	Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☒ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	0.02	0.52	0.31
% of “rejects”	0.07%	1.94%	1.16%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☒ No☐	Yes ☒ No☐	Yes ☒ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 15. Printed and uncoated paper - Digital printing results

The second sample for the digital printing technology is also manufactured using 280 g paper, printed with regular ink, and coated with PU coating, providing the material with a glossy surface, flexibility and strength as described in section **2.2 Types of inks and coatings**. Results on the three performed repulpability tests show a higher percentage of rejects, with an 8% average or 2.10 g of material unfit to be reintroduced into the paper-making process.

Table 10. Repulpability test results – Digital printing paper: printed and coated.

Results			
TEST NO.:	DP PAPER COATED AND PRINTED		
SAMPLE:	2.		
	Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☒ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	2.18	2.09	2.05
% of “rejects”	8.15%	7.81%	7.66%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☒ No☐	Yes ☒ No☐	Yes ☒ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 16. Printed and coated paper - Digital printing results

Results of the two digital printing samples against the control sample are shown in **Figure 17**, where significant impact on the amount of rejected material can be directly related to the addition of coating materials to the product. For example, test 1 of the control sample versus test 1 of the printed and coated sample show a difference of 2.17g of net rejects whereas the same test between the printed and uncoated paper against the control material shows a 0.01g difference in generated rejects. This can be understood as an average reduction of 7.83% in repulpable material after PU coating is applied, however, results also show that even if the percentage of recovered and reusable material is lower, it is still within the repulpability thresholds established by the FBA. The complete results of the comparison between the control sample and the digital printing samples can be seen on **Table 11**.

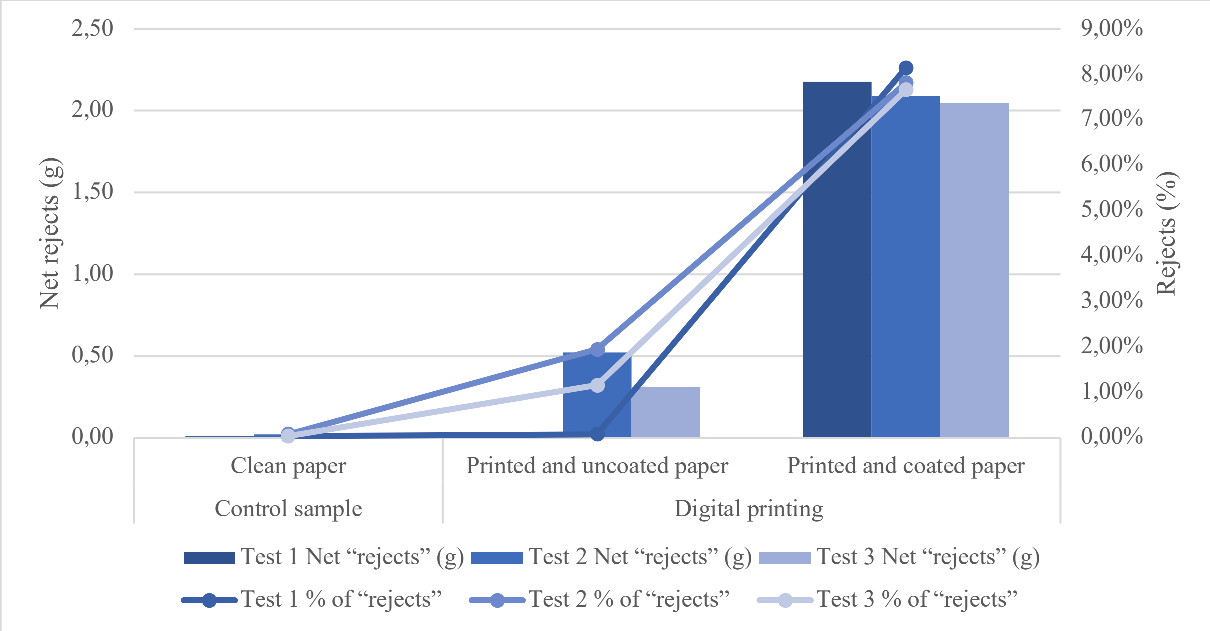

Figure 17. Digital printing samples & control sample

Table 11. Difference in g of net rejects from Digital printing technologies

SAMPLE		**Control sample**	**Digital printing**	**Difference between control sample and DP printed and uncoated (g)**	**Control sample**	**Digital printing**	**Difference between control sample and DP printed and coated (g)**
		Clean paper	**Printed and uncoated paper**		**Clean paper**	**Printed and coated paper**	
Test 1	**Net "rejects" (g)**	0.01	0.02	-0.01	0.01	2.18	-2.17
	% of "rejects"	0.04%	0.08%		0.04%	8.15%	
Test 2	**Net "rejects" (g)**	0.02	0.52	-0.50	0.02	2.09	-2.07
	% of "rejects"	0.07%	1.94%		0.07%	7.81%	
Test 3	**Net "rejects" (g)**	0.01	0.31	-0.30	0.01	2.05	-2.04
	% of "rejects"	0.04%	1.16%		0.04%	7.66%	

4.1.2. Offset printing cardboard packaging

The first sample of Offset printing technology for cardboard packages was sourced from a cosmetic product. This packaging is manufactured on 300 g cardboard, printed using UV paint and coated with UV technologies; additionally, the packaging includes a gold foil finish. As seen on **Table 12**, the first test yielded a 2.21% of reject material, while the second resulted in 2.62% of rejects, therefore the packaging can be regarded as repulpable with a high degree of material recovery fit for the manufacturing of new packages.

Table 12. Repulpability test results – Offset printing: UV paint and UV varnish with gold foil

Results			
TEST NO.:	UV paint and UV varnish - Gold foil 300 g		
SAMPLE:	1.		
	Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	0.59	0.70	-
% of “rejects”	2.21%	2.62%	0.00%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 18. UV paint and UV varnish with gold foil

The second sample was sourced from a food product, whose packaging was manufactured using 260 g cardboard, printed using UV paints, and coated with dispersion varnish. The packaging does not include any other additions and/or decorations. Results of the repulpability tests show that the material falls within the threshold of repulpability, with 3.97 g or 14.84% of net rejects from test 1, and 4.00 g or 14.95% of net rejects from the second test.

Table 13. Repulpability test results – Offset printing: UV paint and dispertion varnish

Results				
TEST NO.:	2. UV paint and dispersion varnish - 260 g			
SAMPLE:	2.			
		Set #1	Set #2	Set #3 (if required)
Is the sample representative of the material as a whole?		Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
FINISHED SAMPLE				
Total over dry weigh (g)		26.75	26.75	26.75
Net "rejects" (g)		3.97	4.00	-
% of "rejects"		14.84%	14.95%	0.00%
Conclusion: Is sample rated as re-pulpable (yes or no)		Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%				

Figure 19. UV paint and dispertion varnish

The third sample of Offset printing technology comes from a line of scientific instrumentation products, reagents, and consumables, whose packaging is manufactured making use of 400 g cardboard, UV printing inks and UV coatings. In terms of repulpability, the conducted tests show an average material reject of 3.28 g of paper or 12.24%, rendering the material repulpable according to the FBA threshold of 15%.

Table 14. Repulpability test results – Offset printing: UV paint and UV varnish

Results			
TEST NO.:	3. UV paint and UV varnish - 400 g		
SAMPLE:	3.		
	Set #1	Set #2	Set #3 (if required)
Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	3.35	3.20	-
% of “rejects”	12.52%	11.96%	0.00%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 20. UV paint and UV varnish

The fourth sample corresponds to a food product printed on 250 g cardboard and employing simple paint and dispersion varnish with no engravings, additions and/or decorations. According to the results of both tests, the combination of the offset printing technique along with the ink and dispersion varnish make up a repulpable packaging with an average reject turnout of 3.81% or 1.02 g.

Table 15. Repulpability test results – Offset printing: Simple paint and dispertion varnish

Results	
TEST NO.:	4. Simple paint and dispersion varnish – 250 g
SAMPLE:	4.

	Set #1	Set #2	Set #3 (if required)
Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	0.97	1.07	-
% of “rejects”	3.63%	4.00%	0.00%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 21. Simple paint and dispertion varnish

Finally, the fifth sample of offset printing packaging was sourced from a cosmetic product. This sample is characterised for making use of 300 g cardboard, UV inks, dispersion varnish and including a metallised engraving. Results of the repulpability testing show that the net rejects can make up to 5.21 g of material or 19.48%, making the packaging unsuitable for repulping, recycling, and manufacturing of new packaging from recycled fibres.

Table 16. Repulpability test results – Offset printing: UV paint and dispersion varnish with metallised engraving

Results			
TEST NO.:	5. UV paint and dispersion varnish – 300 g		
SAMPLE:	5.		
	Set #1	Set #2	Set #3 (if required)

Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	5.21	4.93	
% of “rejects”	19.48%	18.43%	0.00%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☐ No☒	Yes ☐ No☒	Yes ☐ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 22. UV paint and dispersion varnish with metallised engraving

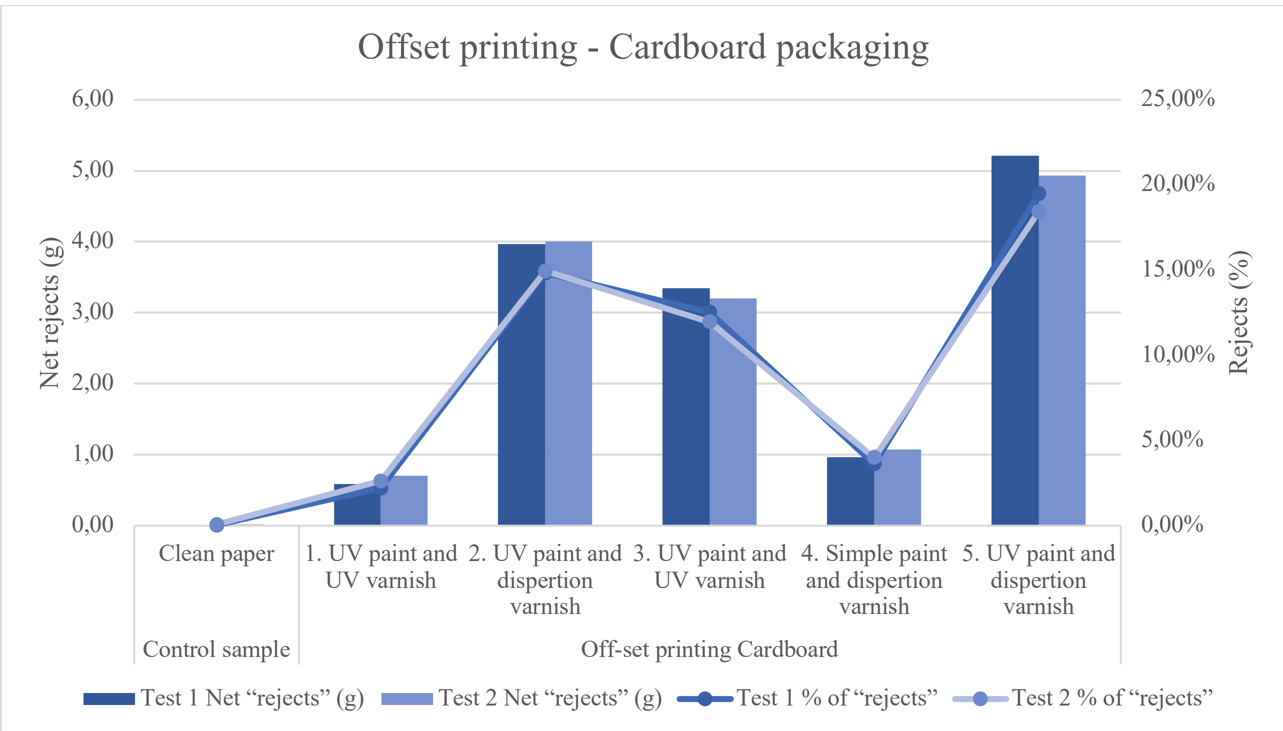

Figure 23. Offset printing - cardboard packaging vs control sample

Full results of the five assessed samples for the offset printing technology compared against the control sample are shown in **Figure 23**. Out of the five samples only **number 5. UV Paint and dispersion varnish with a metallised engraving**, printed on 300 g carton resulted unfit for repulpability due to the high percentage of reject turnout. On the other hand, sample 1**. UV paint and UV varnish** reported the lowest reject production with only 0.59 and 0.70 g of rejects in tests one and two respectively.

Table 17. Difference in g of net rejects from Digital printing technologies

SAMPLE		Control sample	1. UV paint and UV varnish	Control sample vs Sample 1 (g)	2. UV paint and dispersion varnish	Control sample vs Sample 2 (g)	3. UV paint and UV varnish	Control sample vs Sample 3 (g)	4. Simple paint and dispersion varnish	Control sample vs Sample 4 (g)	5. UV paint and dispersion varnish	Control sample vs Sample 5 (g)
Test 1	Net “ rejects” (g)	0.01	0.59	-0.58	3.97	-3.96	3.35	-3.34	0.97	-0.96	5.21	-5.20
	% of “ rejects ”	0.04%	2.21%		14.84%		12.52%		3.63%		19.48%	
Test 2	Net “ rejects” (g)	0.02	0.7	-0.68	4.00	-3.98	3.20	-3.18	1.07	-1.05	4.93	-4.91
	% of “ rejects ”	0.07%	2.62%		14.95%		11.96%		4.00%		18.43%	

4.1.2.1. UV paint and UV varnish

Out of the five samples of cardboard packaging, two employ both UV paint and UV varnishes, namely the sample sourced from the cosmetic product (Number 1), and the scientific instrumentation products, reagents, and consumables (Number 3), the first one utilising 300 grammage paper and the second 400 grammage paper. Additionally sample number 1 includes a gold foil addition, while the specifications for sample 3 report no additions.

Table 18. Repulpability results of UV paint and UV varnish samples

Sample number		Specifications		Test 1		Test 2	
		Carton grammage	Additions	Net “rejects” (g)	% of “rejects”	Net “rejects” (g)	% of “rejects”
UV paint and UV varnish	1.	300	Gold foil	0.59	2.21%	0.7	2.62%
	3.	400	No additions	3.35	12.52%	3.20	11.96%

The repulpability results shown in **Table 18** and **Figure 24** show that both samples classify as repulpable due to the percentage of collected rejects. However, it is worth mentioning that a significant increase in rejects was obtained between samples 1 and 3, with and average increase of 9.83% in sample 3, which makes use of a higher density of paper and includes no additions and/or decorations in the packaging.

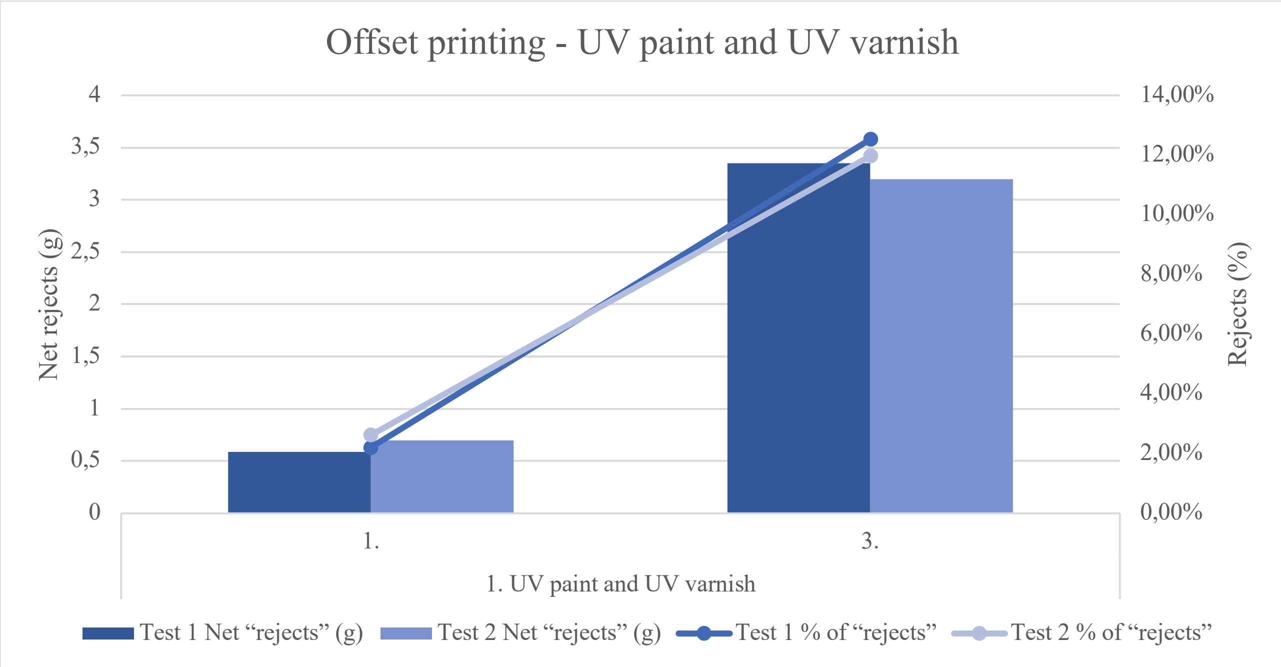

Figure 24. Offset printing: UV paint and UV varnish comparison

4.1.2.2. UV paint and dispersion varnish

The two samples utilising UV paints and dispersion varnish show the following specifications:

Sample 2. – Packaging for a food product printed on cardboard with a 260 grammage using UV paints and dispersion varnish with no additions and/or decorations. Testing concluded the material is fit to repulp with an average reject turnout of 14.90% or 3.99 g.

Sample 3. – Packaging for a cosmetic product. The packaging is manufactured using 300 grammage cardboard, printed making use of the offset technology with UV inks and dispersion varnish, additionally the box includes a metallised engraving. Both performed tests resulted in a reject yield above 15%, rendering the material unfit to be repulped.

Table 19. Repulpability results of UV paint and dispersion varnish samples

Sample number		Specifications		Test 1		Test 2	
		Carton grammage	Additions	Net "rejects" (g)	% of "rejects"	Net "rejects" (g)	% of "rejects"
UV paint and dispersion varnish	**2.**	260	No additions	3.97	14.84%	4.00	14.95%
	5.	300	Metallised engraving	5.21	19.48%	4.93	18.43%

The comparison of both samples shows that the combination of offset printing, UV inks and dispersion varnish yield a high percentage of rejects, however the inclusion of the metallised engraving may be closely related to the 4.64% and 3.48% increase in rejected material between tests one and two of the described samples, thus sample number 5 may be classified as not fit for repulpability and manufacturing of new packaging.

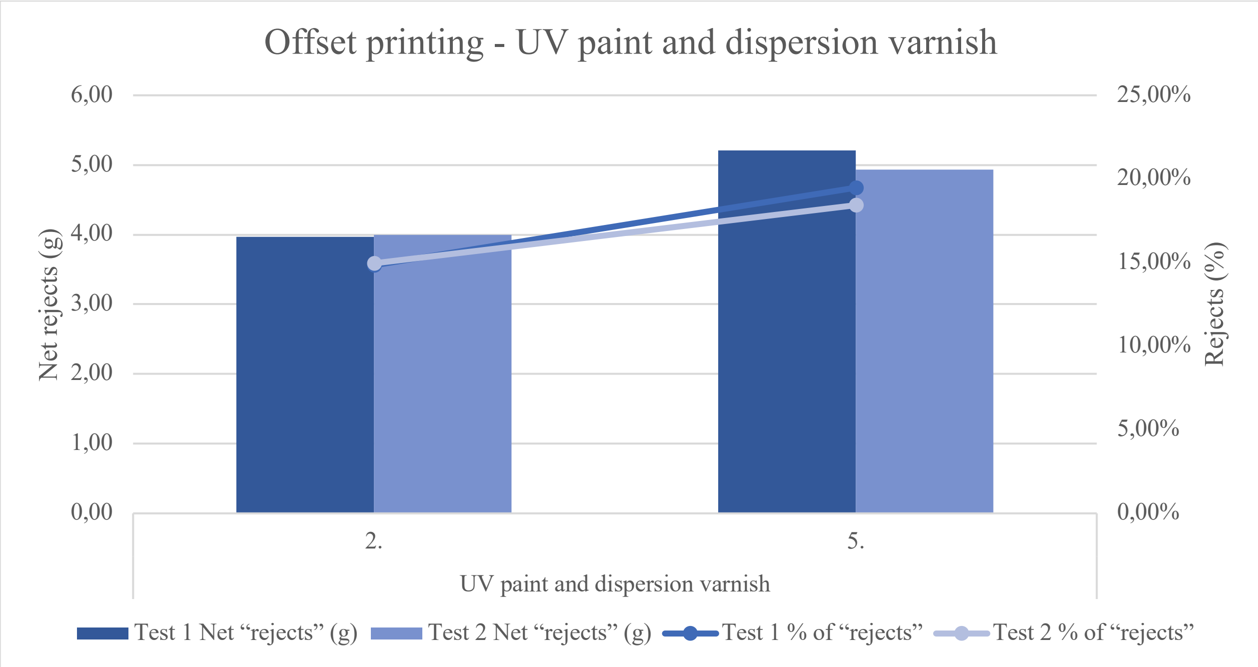

Figure 25. Offset printing: UV paint and dispersion varnish comparison

4.1.3. Offset printing paper labels

Three samples were selected to evaluate the repulpability of paper labels using the offset printing technology. The first of the three samples were sourced from a line of beverages, printed using simple paint on paper of 70 g, and no added varnish. According to the repulpability test results, neither the paint nor the printing technique has a significant impact on the amount of recoverable cellulose, since as seen on **Table 20**, the net rejects from test number 1 resulted in 2.15 g, and 2.45 g on test 2 or 8.04% and 9.16%, respectively. It is then possible to conclude that the “Bruza” labels are fit for repulpability.

Table 20. Repulpability test results – Offset printing: Plain label - Simple paint without varnish

Results				
TEST NO.:	1. Plain label - BRUZA			
SAMPLE:	1.			
		Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?		Yes ☒ No☐	Yes ☒ No☐	Yes ☒ No☐
FINISHED SAMPLE				

Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	2.15	2.45	
% of “rejects”	8.04%	9.16%	0%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 26. Plain label, Simple paint without varnish

Sample two is a metallised label printed through the offset technique using foil paint and no varnish on 68 grammage paper with no additional decorations for the “Taurus” beverage, according to the provided specifications from the manufacturing company Trustpack. Opposite to the previous sample, the testing resulted in 43.85% and 52.49% of rejects or 11.73 g and 14.04 g for tests 1 and 2, which as stated by the FBA is considered as not fit for recovery, recycling, and manufacturing of new packaging materials. It is worth noting, that the specification of all three offset printing paper labels do not include any type of varnishes and/or coatings, therefore it is possible to conclude that the change in net rejects is directly related to the type of paint used for its manufacturing.

Table 21. Repulpability test results – Offset printing: Metalized label, Foil paints without varnish

Results			
TEST NO.:	2. Metalized label Foil paints without varnish -		
SAMPLE:	2.		
	Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?	Yes ☒ No☐	Yes ☒ No☐	Yes ☐ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net “rejects” (g)	11.73	14.04	

% of "rejects"	43.85%	52.49%	0%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☐ No☒	Yes ☐ No☒	Yes ☒ No☐
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 27. Metalized label, Foil paints without varnish

Finally, sample three is described as a plain label using simple paint, a gold foil decoration, and no varnish, printed on paper with a grammage of 70 utilised for a beverage. Similarly to the previous sample, the repulpability tests resulted in the label being unfit to be repulped due to the percentage of rejects recorded on both performed tests being over 15%. This translates into 4.11g of net rejects for test one and 4.06 g for test 2.

Considering that the specifications for sample one and three only differ in the inclusion of a gold foil decoration on the latter sample, it is possible to conclude that this addition is directly linked to the increase in net rejects from one sample to the next.

Table 22. Repulpability test results – Offset printing: Plain label, Simple paint without varnish, and with gold foil

Results			
TEST NO.:	3. Plain label Simple paint without varnish & gold foil		
SAMPLE:	3.		
	Set #1	**Set #2**	**Set #3 (if required)**
Is the sample representative of the material as a whole?	Yes ☐ No☐	Yes ☐ No☐	Yes ☐ No☐
FINISHED SAMPLE			
Total over dry weigh (g)	26.75	26.75	26.75
Net "rejects" (g)	4.11	4.06	-

% of "rejects"	15.36%	15.18%	0%
Conclusion: Is sample rated as re-pulpable (yes or no)	Yes ☐ No☒	Yes ☐ No☒	Yes ☐ No☒
NOTE: The sample passes if the percentage of Rejects is less than 15%, rounded to the nearest 0.1%			

Figure 28. Plain label, Simple paint without varnish, and with gold foil

The full results of the three offset printing paper labels are presented in **Figure 29**. As opposed to the samples selected both for digital printing and offset printing for cardboard packaging, two out of the three samples recorded a net rejects turnout of more than 15%, which as stated throughout this document, renders the packaging material as unsuitable for repulping. Out of the three labels, sample number two using foil paint records the highest percentage of rejects, with a maximum of 52.49% or 14.04 g.

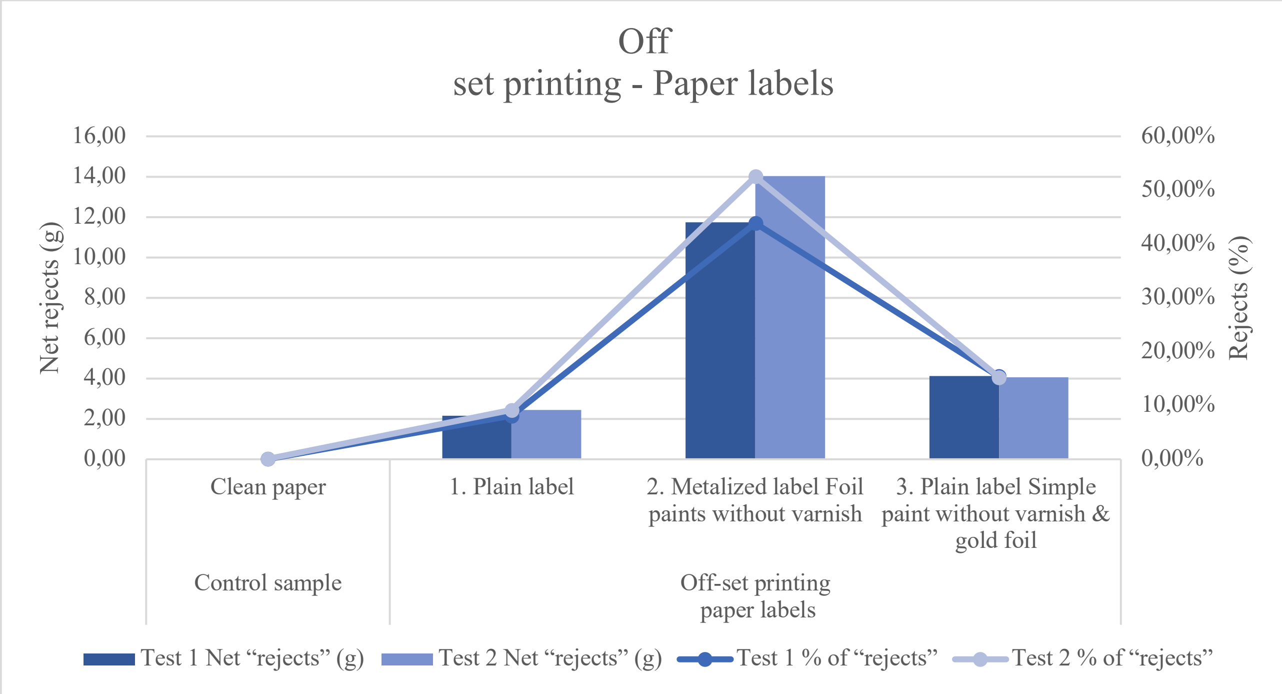

Figure 29. Offset printing – paper labels vs control sample

4.2. Life cycle assessment (LCA) review and discussion

As stated in section 2 State of the art on fibre recovery and quality, the manufacturing of paper and cardboard packaging utilises large amounts of recycled cellulose as raw material, which according to current research can be utilised and re-introduced into the productive process up to seven (7) times in order to conserve the material's integrity and quality [29] [30].

LCA studies like the one conducted by [31] where three types of packaging materials used for the transportation of food products including a composite packaging made out of High Density Polyethylene (HDPE) using natural fibres, a HDPE packaging without natural fibres, and a single use cardboard box, concluded that even if a more durable packaging material using HDPE is developed and introduced into the market, it would be necessary to reuse the material at least 29 to 35 times to achieve a break-even in greenhouse gas (GHG) emissions. This is mainly due to the end-of-life treatment options available in Brazil and Europe, where the first country mainly opts for landfilling and incineration [31].

Similarly, an LCA of cellulose packaging materials specifically targeting folding box board and kraft liner paper developed by [32], assessed the cradle to gate impact of the products on biotic resource depletion, global warming potential, human toxicity among others. While the inventory analysis included the addition of couchê inks and starch coatings, no information about their impact on the environmental performance of the finished products was included in the conclusions or result discussion.

Interestingly, the industry has seen a couple of research papers targeting the environmental performance of recovery options for the repulping reject from different types of packaging and possible treatment processes available. For example, [33] used LCA to compare three treatment processes available for the management of 1 tonne of repulping rejects, which included incineration, chemical recycling, and mechanical recycling. Once again, the research excluded any mentioned of the impact of inks, coating, and varnishes which in this case might not be as representative since the functional unit considered is 1 tonne of liquid packaging board (LPB) made up of 70% plastic, 25% fibre, and 5% aluminium.

Other studies focusing on packaging waste treatment have been carried out mainly comparing the performance of waste management facilities handling the end-of-life stages of paper and plastic packaging. [34] evaluated the environmental performance of waste treatment for mixed plastics and mixed paper and packaging employing either landfilling, incineration, or gasification-pyrolysis (GP). As a result, the study concluded that treatment of mixed packaging through landfilling generated the lowest single score, further proving the need to manage different waste streams through different technologies.

It is worth noting that from the reviewed LCAs little to no information and assessments were made in terms of printing technologies used, coating materials implemented, and addition of any decorations included in the finished products. This could be related to the lack of available data on the composition of inks, coatings, and varnishes, along with current interest within the industry to reduce the amount of used inks through the implementation of colour reproduction technologies, as presented by [35].

Conclusions and recommendations

1. Different types of printing technologies are applied for the manufacturing of packaging, with flexography, digital, and offset printing being the most widely used within the consumer products industry due to the wide array of inks available for use.
2. Legal requirements currently applicable to FCMs as well packaging meant for cosmetic and pharmaceutical products within the EU do not include specifications on inks, varnishes, coating, and other additions to the finished product, nor are they addressed in regulation concerning packaging waste. Further updates on such topics could significantly incentivise research and development of alternative materials of a more environmentally sustainable nature.
3. Although several testing methodologies are available within the packaging industry, the most widely accepted include the FBA Voluntary Protocol and the CEPI recyclability laboratory test, both of these methods establish a reject threshold of 15% and 20% respectively, providing packaging designers with a working framework to develop and propose packaging solutions.
4. Three out of the nine assessed samples reported a percentage of rejects above 15%, meaning that according to the FBA testing method, the combination of printing technologies, paints and varnish yield the material unfit for repulping, recycling, and manufacturing of new packaging.
5. While the addition of inks can have a degree of impact on repulpability, the percentage of rejects will be no higher than 1 g. On the other hand, the addition of the PU coating resulted in a reject yield of 2.10 g of material on average, significantly reducing the amount of recoverable cellulose.
6. When comparing the two samples using UV paint and UV varnishes, no visible pattern was identified. On the contrary, sample 1 which included a gold foil addition reported an average of 2.41% rejects while sample 3 which included no additions to the packaging reported an average of 12.24% rejects.
7. The two samples utilising UV paint and dispersion varnish show similar results in terms of net rejects, with sample 2 resulting in 3.97 g and 4.00 g of net rejects, and sample 5 reporting 5.21 and 4.93 g. However, the addition of metallised engravings to the latter sample could be linked to the negative repulpability results.
8. Out of the 3 tested paper labels using the offset printing technology, 2 record a reject percentage of over 15%. These results can be linked to the use of foil paints and varnishes for their manufacturing, as well as the low grammage of paper used in the manufacturing process.
9. The tests performed assessed the repulpability of samples utilising conventional inks and coatings, however, as described in section 2.2 Types of inks and coatings, major research is being done to better understand and develop the use of bio-based materials as raw material for inks, coatings and varnishes. This gives room to perform similar research to the one presented throughout this document, and therefore determine the impact of said materials on the repulpability, recyclability and circularity of packaging.
10. Little research has been carried out tackling the environmental performance of inks, coatings, and varnishes currently applied within the packaging industry. This can in part be attributed to the limited publicly available information on the composition of said mixtures as well as the little to non-existing inclusion of these type of chemicals in existing LCA software, further preventing the development of independent LCAs to determine their impact throughout different life cycle stages.

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