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Review

Polymer Banknotes: A Review of Materials, Design, and Printing

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Abstract: Nowadays, more than 45 countries in the world use polymer banknotes in their monetary and banking systems. It is expected that by 2030, another 20 countries will abandon the use of paper banknotes and switch to polymer banknotes. Recent research shows that several countries in the Middle East and the European Union will switch to printing and using polymer banknotes soon due to the advantages of polymer banknotes. Polymer banknotes are made of polymeric materials. They possess very special optical security features and promote sustainability in the world, which motivated us to review recent materials, design, optical technologies, and printing methods in this respect. Since the topic of polymer banknotes is new and there are not many articles and research about them, this review specifically focuses on the structure of the constituent materials and security features and their reuse with an emphasis on sustainability and environmentally friendly banknotes. Specifically, analyses of 3D polymer films and the security properties of polymer banknotes are carried out. Finally, comparison studies with paper banknotes are performed, and pertinent conclusions are outlined.

Keywords: polymer banknote; thin layer polymer films; design; printing; sustainability

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1. Introduction

By the beginning of the 21st century and the increase in the planet's population, the improper use of natural resources and the destruction of the environment by humans caused problems. Chemicals and environmental pollution, and the use of chemicals and their return to nature such as petrochemicals that have destructive effects, can cause irreparable damage to our living environment. However, the main topic discussed in this article is using natural and synthetic fibers and materials to produce banknotes that we use every day. The current banknotes used in most countries use the primary materials of wood pulp, cotton fibers, and synthetic fibers of thin fabrics which directly harm the environmental resources. They have little resistance to tearing and lose their resistance very quickly against factors such as temperature changes [1–4].

At the end of the 20th century, with the expansion of polymer nanotechnology and its increasing use in daily human life, the subject of material science, recycled materials, environmental protection, and the expansion of green energies have been significantly explored [1]. The first studies on polymer banknotes began in 1968 in Australia, specifically with the help of the scientific and industrial organization of the commonwealth of independent states (CSIRO), and then in the United Kingdom and more than 40 countries. The world found its way, and thus a new era of polymer banknotes entered our daily lives [1].

Polymer banknotes and their constitutive materials are novel and expandable subjects. Consequently, new countries are moving towards using such banknotes, and more studies are directed to expand how to design them better for cost saving, minor damage to the environment, and recyclability of the material.

This paper addresses three essential principles that were the root of the formation of polymer banknotes. These three critical principles are: (1) increasing the security factor, (2) analysis of polymer materials that increase the durability and reduce the costs of banknote production, and (3) emphasizing green technology (green energy) and environmental problems [5,6].

The countries which use polymer banknotes while writing this paper are mentioned in Table 1 and displayed in Figure 1 based on information from the Wikipedia website [7].

Table 1. Countries using polymer banknotes.

England	U.A.E	Canada	Australia	Vietnam
Egypt	Angola	Mexico	New Zealand	Romania
India	Albania	Sri Lanka	South Africa	Thailand
Islands	Chile	Nicaragua	Lebanon	Nicaragua
Israel	Brazil	Singapore	Uruguay	Northern Ireland
China	Philippine	Honduras	Guatemala	Indonesia
Solomon	Scotland	Nepal	Libya	Paraguay
Saudi Arabia	Haiti	Kuwait	Morocco	Namibia
Russia	Brunei	Poland	Nigeria	Maldives

Figure 1. Countries which use polymer banknotes.

2. Materials in Polymer Banknotes

In discussing the ingredients of polymer banknotes, which is a kind of revolution in the production of banknotes, and the unique features of this banknote model, many countries were encouraged to use polymer banknotes for various reasons. It should be borne in mind that the environmental and security factors of polymer banknotes that make this banknote model different and better than other cases all depend on the unique materials, composition, and design of polymer banknotes.

It should be noted that the materials used to make polymer banknotes from certain compounds have been designed by large companies and large training centers in the world, and even some formulas and instructions for its formation have been confidential to date. Yet, the results of research and development on polymer banknotes have led to the discovery of many ingredients in these banknotes, which we will discuss in detail in the constituents of polymer banknotes [8,9]. Apart from the constituents of paper banknotes that are harvested directly from the environment, the type of paper banknotes and their strength is highly questionable because the paper banknotes that are in circulation have very little resistance to damage, which in some cases are addressed as below.

In paper banknotes, old materials such as cotton and fabric fibers are used parallel to the lines of banknote paper, which causes the premature rupture of banknotes. Yet in polymer banknotes, there are three layers of polymer film and also the triangular shape of the fibers. Moreover, the vertical design with banknote lines reduces the rupture rate of polymer banknotes. It should be noted that paper banknotes do not have any transparency because they widely use cotton fibers and wood pulp, and their heat absorption rate is very low if exposed to heat. They react very quickly. The network structure is destroyed and deformed, and the banknote loses its function. However, due to polymer films' presence in the polymer banknote's structure, more heat is absorbed and therefore, deformed and collapsed. The structure of polymer banknotes is not straightforward [3,4]. There is a change in the structure and an increase in the length of failure of paper banknotes for various reasons and over time. As a result, more countries cause more and more environmental damage [9].

Concerning the discussion of the constituents of polymer banknotes, their structure should be carefully examined. For example, the 5-pound polymer banknote uses three layers of a transparent polymer film with very high flexibility, which explained by three layers of polymer film where two side films are made of biaxial-oriented polypropylene (BOPP), which is connected to the middle layer or film in two axes. The middle layer can also be made of polypropylene or polyolefin polymer film or be a composite of these films [10,11]. The paper and polymer 5-pounds UK banknotes can be seen in Figure 2, which shows the different appearances. It should be noted that the middle layer is due to the porosity of heat and moisture. Therefore, polymer banknotes have very high resistance and durability against temperature changes and bursts. These factors and standards of polymer banknotes are based on the international standard S.C.A. All of these cases have been verified over the years. Polymer banknotes are much cleaner and more transparent than paper banknotes because they do not use wood fibers or pulp in their ingredients [12,13].

Figure 2. The 5-pounds banknote in England: (**a**) paper banknote, (**b**) polymer banknote.

Another effort of the polymer industry is using polymers in producing paper and its replacement instead of pulp paper. Various solutions regarding the use of polyolefins (synthetic fibers) have been proposed, which are obtained by combining polypropylene (PP) and different minerals in specific proportions of plastic sheets with similar properties to ordinary papers [14,15].

Due to the surface characteristics of the polymer substrates, some of the currently used fingermark enhancement techniques for the currency may become obsolete as a result of the UK's recent move to polymer banknotes. Polymer banknotes require alternate processes due to their non-porous surface with some semi-porous properties. This preliminary study looked into recovering fingermarks from polymer notes using vacuum metal deposition with elemental copper [16].

Compared to paper sheets, plastic sheets are durable in all atmospheric conditions. One of the properties of this type of paper is that it is waterproof. The ordinary paper needs to be covered with polyethylene in the mold opening on its surface for waterproofing and to get the desired and beautiful result in printing. It must be laminated with three-dimensional polypropylene, which must be glued and recycled. It makes it impossible, but the synthetic film has all these properties. This new product has typical paper features in printability, post-printing operations, and plastic regarding waterproofness and resistance to decay and tearing. Synthetic paper is widely used in cases where durability are essential in printed products. It is used continuously and regularly or exposed to natural factors and moisture [12,13,17].

In different thicknesses (from 80 micrometers to 800 micrometers), it is a suitable alternative to ordinary paper and cardboard, as well as PVC and PP in the printing, packaging, and the advertising industry. Synthetic paper and cardboard are made of a completely waterproof polymer. It is possible to write on ordinary paper, and printing, binding, punching, letterpress and die-casting, thermal and ultrasonic sewing, vacuum, all kinds of UV and varnish, laminate, and perforation on these papers are easy. Plastic paper is 100% waterproof as shown in Figure 3. It is used in wet places and places that deal with water and humidity. In products that deal directly and indirectly with water and moisture, such as various bottles and packaging of protein materials, etc., the use of plastic paper as usual or its sticky back has a special place due to its washable feature. Resistance to tearing and decay, durability, and long life should also be added. While reducing long-term consumer costs, this feature will reduce paper waste and save the whole country in taking full advantage of this synthetic paper.

Figure 3. The waterproof polymer banknote.

Chemical resistance acids, oils, and other chemicals in the presence of papers have a destructive effect on them. In contrast, polymer paper is resistant to these substances due to its plastic properties. Plastic paper based on polyolefin films such as polyethene and polypropylene has been popular and proven for paper manufacturers and printers in the last decade. This study investigates sheets prepared from polyvinyl chloride/acrylonitrile-butadiene rubber (PVC/NBR) to provide a surface that meets the writing properties [5,6,12,14,18].

Polymer banknotes are not destroyed in water and their physical condition does not change. The transparency of polymer banknotes is due to the materials used in their composition and the security factor of this model of banknotes is very highly water-resistant [17].

Water and moisture can penetrate even into the best cellophane laminate materials. However, the synthetic film can be dipped in water and the moisture wiped off without damaging it. For this reason, the synthetic film is widely used in cases where the printed product can come into contact with water, such as labels on plants and signposts in diving/driving instruction. The synthetic film is the best option for printing materials that can come in contact with water, reducing production time and cost. Paper cellophane takes more time, increasing the costs for a high-durability product and using traditional materials [19].

Because the synthetic film has all the benefits of vinyl and laminate flooring together, it can save both time and money. The tear-resistant synthetic film does not tear. This advantage increases its durability. Some customers use synthetic paper to cover up car operators, restaurant menus, and other items that are constantly in contact with exposure to or under constant pressure. Heat and cold-resistant synthetic papers are not only waterproof but also resistant to cold and heat caused by climate change. This material is used for products for outdoor use that are constantly exposed to pollution, sunlight, cold, wind, etc., as its surface can be cleaned without any damage or discoloration. These products are excellent examples of signs and symbols used in gardens and outdoors. These signs and symptoms do not suffer much in the cases of getting wet, falling mud, being under the feet of passers-by and other cases, and dirt on them can be easily removed. Cleaning synthetic papers is also suitable for writing down sudden ideas and taking notes, as pencil writing can be erased with an eraser. The ability to receive digital printing is perhaps one of the most exciting features of synthetic print materials [20].

Production of current banknotes has many complicated processes, and the usage of multiple layers of ink and the application of NGB features make the production cycle more complex with new security features and changes in design. For more security features in the next generation of Australian cash, more than 200 features were evaluated based on flexibility, safety, performance, durability, ease, and cost of production. In addition, to take advantage of the opportunities offered by the polymer substrate, the new banknotes include advanced window security printing technologies with much more sophisticated designs than in the current series [6,17]. The new banknotes also have up-to-date offset printing techniques and have a hit quality. As part of the design process, the bank consults with designers, artists, and historians to ensure that the new banknotes are functional and recognizable and reflect Australia's cultural identity. Accordingly, it was decided to preserve many of the salient features of the current series, including those formed in the photographs, size, general color palette, and religious structure. An important decision in this regard is the bank's commitment to helping the visually impaired community, which relies on size differences and bold symbols to distinguish between different names. The bank is also aware of the many devices that accept banknotes and the benefits of manufacturers and users of these machines maintaining religious size and structure. At the final design stage, the printing bank experiments with the printer. These tests aim to identify and resolve any manufacturing issues and ensure banknotes are ready for mass production. The banknotes produced in these trials provide the bank with aesthetic, machine-readable, and durable banknotes and allow the bank to use the general equipment and banknotes considerably softly [9,13,17,20,21].

3. Polymer Banknotes Features

Some features are especially important in the design and production of polymer banknotes, and are mentioned below.

3.1. Transparency

It starts by applying a layer of ink on transparent polymer sheets made with a special process. This helps the other layers adhere better to the polymer.

3.2. Offset Printing

The sheets are then printed by offset printing, which simultaneously applies colored inks to both sides of the sheet. In this way, the images on both sides of the banknote are aligned. This process provides the basis for the application of one of the key security features of Australian banknotes (with banknote authentication). When light reaches the banknote, diamond-shaped patterns are printed on each side of the banknote to create an image of a seven-pointed star inside a circle [22–24].

3.3. Numbering

The unique serial number is then printed on the banknotes using ink that is fluorescent under ultraviolet light.

3.4. Coating

Before the sheets of banknotes are cut into single banknotes, a protective coating is applied to the bull for longer durability and to keep it clean. Fluorescent sections are also applied at this stage.

3.5. Final Banknotes

The banknotes are re-examined to be free of any errors during the printing process. They are then packaged and prepared for invoicing [24].

4. Design Requirements

According to New Zealand bank information, they have some important matters regarding the design of a banknote. In this section, the critical points of the design of modern banknotes in New Zealand are studied and the results are mentioned in Figure 4 below and explained.

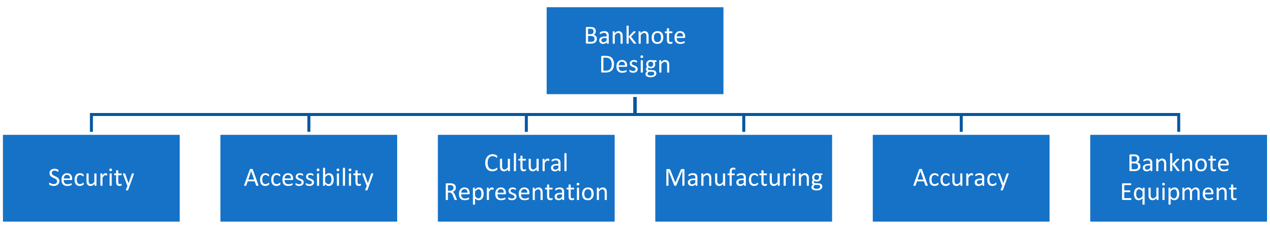

Figure 4. Design of polymer banknotes.

4.1. Security

Security features must be robust in two different ways. They must, first and foremost, be challenging to duplicate. Second, they must be simple for the general public to verify. A banknote must incorporate the proper selection of security measures into the appropriate substrate. The underlying substance on which the patterns are printed is referred to as the "substrate". The polymer substrate has been used in New Zealand banknotes since 1999.

4.2. Cultural Representation

Banknotes are sometimes called "a country's business cards" since they hold much weight as symbols of that culture. As a result, the New Zealand people need to be able to relate to the designs and appreciate their creative quality. The Reserve Bank emphasized the link to New Zealand's bicultural background while updating the notes' appearance and modernizing the designs.

4.3. Accuracy

The numerous information depicted on banknotes must remain correct. The existing New Zealand banknotes' central topic is the country's indigenous flora and wildlife, and the new banknotes must reflect these subjects with meticulous care to every last detail.

4.4. Banknote Equipment

The accuracy of the various details shown on banknotes is essential. The fundamental theme of the current New Zealand banknotes is the country's unique flora and animals. These topics must be faithfully reproduced on the new banknotes down to the last detail.

4.5. Manufacturing

Although the printing techniques used to create banknotes are particularly advanced, they nonetheless place limitations on the finished product, just like any other manufacturing process. If these limitations are not considered while designing banknotes, designs that cannot be mass-produced with current printing technology may be chosen.

4.6. Accessibility

Strong contrasts and big typefaces are aspects of an excellent banknote design that help visually impaired persons recognize the banknote's value. This is crucial since visually impaired people must be able to utilize banknotes. This upgrade was a perfect opportunity to address some of the design issues in the current series and make recognition simpler. On the other hand, differentiating the size (both length and height) of notes by denomination is the most effective way to help people who are blind tell the notes apart [25].

In addition, in Australia, the Reserve Bank invited a variety of designers to submit concepts. The designers summarized the design concepts, narrative components, and security features, each with prior experience creating banknotes. Each dominating piece must maintain its original color, size, and direction from the initial set of polymers. Similarly, the numerals etched on the banknotes should be discernible to the blind and partially sighted due to the long-standing relationship with the visible community. The position of other features, such as a portrait, serial number, signature block, religious numerals, phrases, and words, and the objects stated in the abstract are also included. Finally, the designers were instructed to incorporate Australian natural plants, animals, and other aspects that symbolize Australian identity from other cultures. Some characteristics were incorporated into the security features needed for the design concepts, used in the first series of polymers and brand-new features such as holographic gadgets, motion features, multi-lit windows, and OVI components. These abstractions, when appropriate, indicated the features' locations, sizes, levels of complexity, and interconnections with other features. Every studio in Melbourne was chosen by the designer who would give the best design session and successfully integrate the necessary features. Every studio was asked to submit the design thoughts for every section [4,9].

Several printed layers that offer functionality, security, and visual content are used to manufacture banknotes. The transparent top window of the banknote was joined to the bottom window, which was one of the most significant alterations. Although an entire window of the kind present in the new series of banknotes had never been utilized previously, more expansive windows had been the international design trend for polymer banknotes. In terms of manufacturing and money circulation, this design presented difficulties. To demonstrate the readiness to create, design, and the capacity of printing equipment makers to find ways to ensure that their equipment can handle new money, a preliminary test was conducted before the design was authorized. Banknotes are created using many printed layers that provide functionality, security, and visual content. One of the most notable changes was joining the banknote's bottom and transparent top windows. Even though an entire window like the one seen in the new series of banknotes had never been used before, polymer banknotes had been designed with more oversized windows on a global scale. This design faced challenges in production and money circulation. Before the design was approved, a preliminary test was conducted to show that the painting equipment manufacturers were prepared to build, construct, and discover ways to ensure their equipment could handle new money [4,26].

In recent experiments, the NPA developed a method to manufacture a tactile feature to assist those who are blind or have limited eyesight in determining the worth of their banknotes when it enters the Reserve Bank. Preliminary production starts once all production-related issues have been resolved, the design has been completed, and the experiments have been successfully finished. Before the release of the $5 first new series mark on 1 September 2016, 172 million new banknotes were issued by the NPA. Commercial banks can acquire these currencies in face value and numbering [4,10,13,26].

5. Production Stages

There are 13 production stages for new banknotes. Some of these stages are used in the first series of monetary series as well, while others are unique to the new banknotes. They are detailed below.

I. Polymer substrate production: In the process of producing banknotes in Australia and New Zealand, transparent plastic beads are first melted and turned into a large bubble by the blowing process.
II. Film production: Bubble walls are compressed together and cooled to form polyethylene multilayer polymer films [24].
III. Inking: Special colors are used to create a matte film, except for the brown areas to create clear windows before they reach the sheet.
IV. Offset: Background colors and patterns are printed on both sides of the polymer sheet simultaneously on the printing machine once. These machines can print up to 8000 sheets per hour.
V. Foil: Multiple security features are applied in the top–down window as a continuous bar. This is the first unique method for new banknotes.
VI. Screen printing: The effect of rotating color on a screen printing process using variable optical ink is applied in the second unique process [27].
VII. The first stage of 3D printing: The main design elements, such as portraits and narrative elements, are printed using printing machines. In this process, the ink is transferred to high-pressure sheets in the form of engraved metal sheets.
VIII. The second stage of 3D printing: Separate prints are required for each side of the sheet. An updated print result is an important feature of Australian cash. Some small and large features are also produced during this process.
IX. Serial number: The serial number is added to the sheets by the printing process.
X. Coating: A protective coating is used for the flexible printing process (flexography) in the form of banknotes. This coating helps the durability and cleanliness of the plastic cash.
XI. Coating: The touch function is employed in the final printing process for a new generation of banknotes. The touch function was created to assist visually handicapped people in identifying different currencies. This number is composed of several numbers on the long edges of the alphabet adjacent to the top–down window.
XII. Cutting: Printed sheets are cut individually.
XIII. Inspection: Individual banknotes are electronically examined to ensure that their quality meets the acceptable level. The banknotes are then packaged and stored

in containers and stored in a safe room before being distributed throughout the country [13,28,29].

6. Security Factor

There are different aspects of security options in polymer banknotes which can help us increase the security of banknotes compared to new models.

6.1. Optical Membrane Security Assembly with Focused Sensors

An assembly is made for use as a polymer banknote with optical security features. The device consists of a flat substrate consisting of two thin layers or a transparent polymer sheet such as polypropylene. The device consists of an image stack (for example, of several composite layers and other materials) applied to the first side of a flatbed. The optical security assembly provided includes a set of lenses on the first side of the flatbed pictured on the first side adjacent to the stack. The optical security assembly consists of an image element, such as interlocking images, on the other side of the flat platform opposite the lens array. The lenses are each configured to have a focal length corresponding to the thickness of the flatbed and to focus on the other side of a part of the image element to provide "focus on the bed" [5].

These explanations are directed towards the design of polymer banknotes with optical security features, and in particular, banknotes that include optical security assemblies specifically designed to minimize thickness. For instance, optimal presentation is the focus on a blended image while having an overall thickness that matches the adjacent parts of the banknote. Polymer banknotes or currencies are made of plastic or polymer, such as biaxial-oriented polypropylene (BOPP) and blown polypropylene films. A growing number of countries are considering this, or even converting from paper to polymer banknotes, with at least eight countries completely replacing polymer banknotes in 2014. Lower costs become a reason for this replacement as a polymer substrate or body of banknotes makes the currency more durable and longer lasting. However, anti-counterfeiting is another important reason many countries are replacing polymer banknotes [1,11,26].

Banknotes production steps are shown in Figures 5 and 6.

The security features provided on the paper can also be provided on polymer banknotes. In addition, however, new security features that cannot be offered with paper money can be provided with polymer banknotes because the bed or body of the banknotes can be presented transparently (here "Transparent" means semi-transparent to transparent to clear). Hence, a transparent window may be provided that is used to display a security image that allows the banknote to be authenticated. Optical security features may be in the form of a lens or lens array (e.g., a lens array, a diffraction grid, or the like) that is transparent to display an image printed on the opposite side of the substrate.

For example, the displayed or visible image may be a three-dimensional (3D) image or could be an image that is animated. In addition, through a different angle of view, the image is presented with the total size of a pixel map or Moire pattern, and/or provides other optical technologies. With such optical security features, it is tough to counterfeit polymer banknotes, and due to optical security features, it is not possible to simply use scanners, photocopiers, and other methods that are used for some paper banknotes.

In many polymer banknotes, security and anti-counterfeiting features are provided by a lens or array lens that is embossed on the front or back of the banknote (or its transparent part). Some of these features are provided with a relevant image (for example, a print, embossing, holography, or other images visible through a lens or array lens on the back of the banknote). However, as an ongoing challenge, it is required to focus enough with the lens on the image to provide it clearly to a viewer through the lens or lens array. Currently, an existing design for these optical security features provides lenses that are relatively wide and focus on a point far beyond the back of the banknote where the image is presented so that the image is displayed to a banknote authentication viewer [23,27–31].

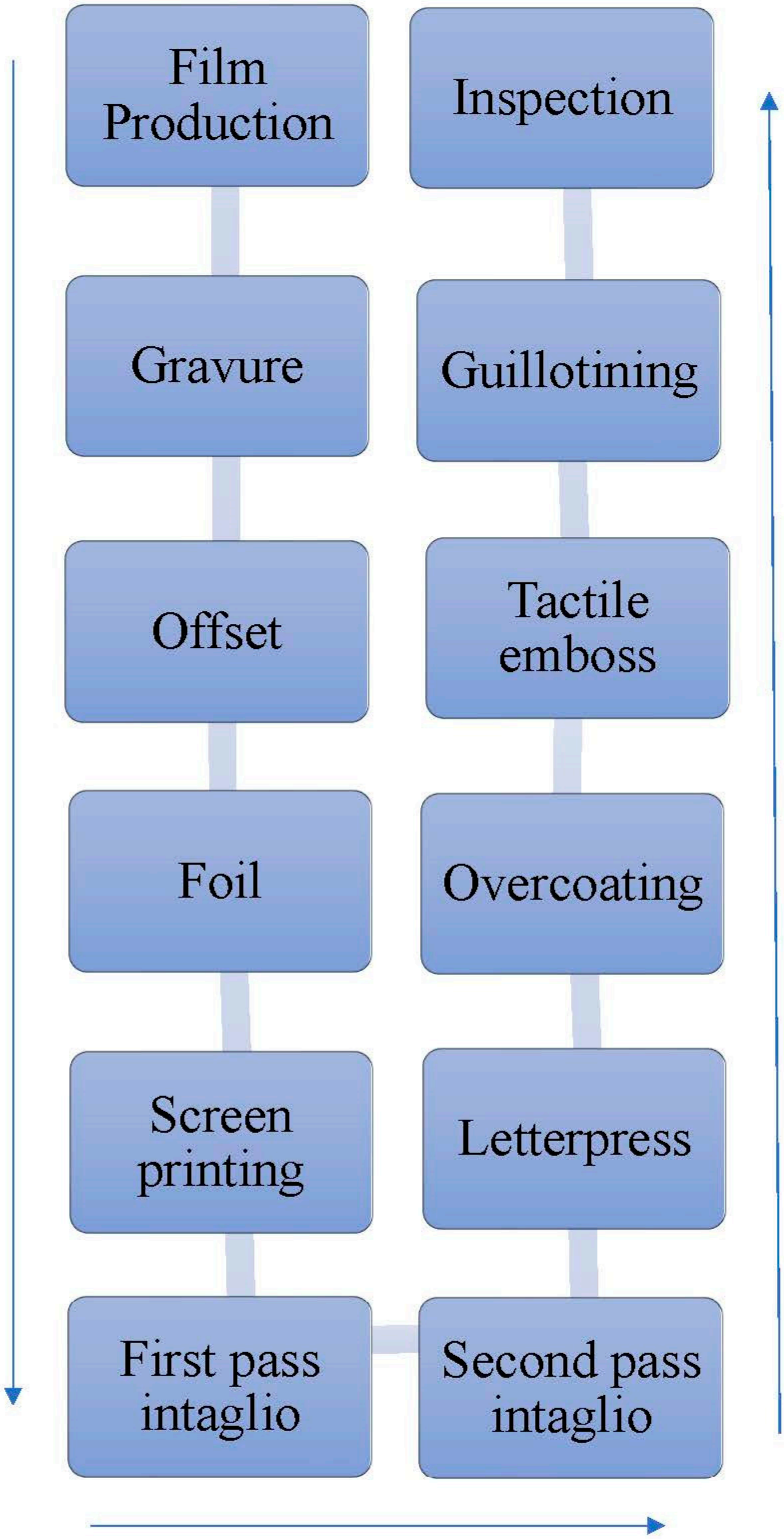

Figure 5. Production stages of banknotes.

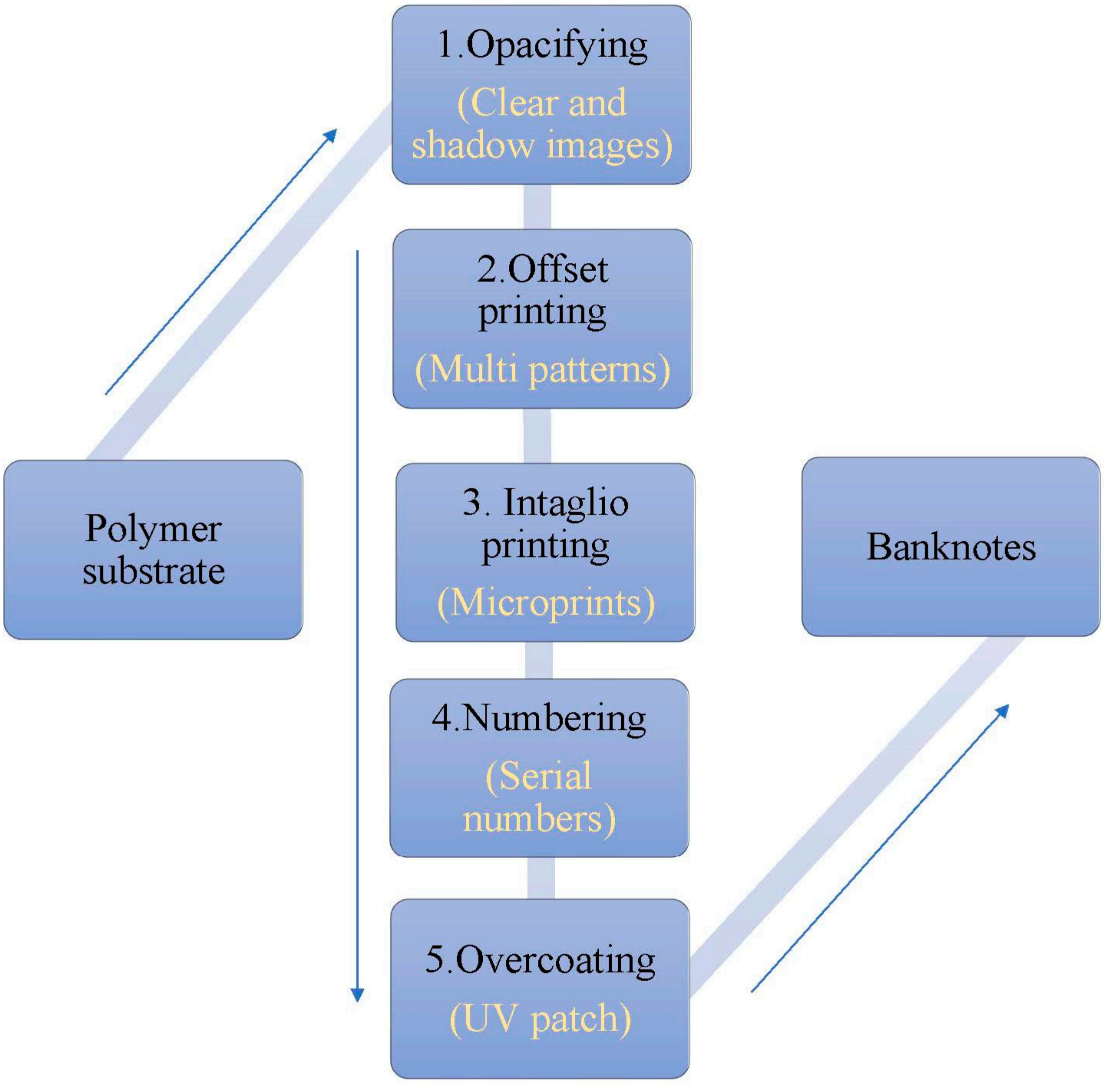

Figure 6. Steps of producing polymer banknotes.

In this regard, many polymer banknotes are in the range of 65 to 100 micrometers. For example, some banknotes have a bed or body that is 75 micrometers thick, while ink and/or other materials deposited on its outer surfaces increase the overall thickness by about 10 to 20 micrometers so that the overall thickness of the banknote is 85 to 95 micrometers. The thickness of the banknote bed material has a fixed ratio for each series of banknotes for each country, and a requirement for each optical security feature is that the thickness of the banknote in the optical security features corresponds to another part of the banknote. For example, the thickness of the substrate is provided by the lens array. Besides, the ink or other material used to display the image on the banknote must be equal to or less than the adjacent parts of the banknote [31].

In addition, the inventor company has realized that the optical security lens assembly array can be provided on the transparent surface of the banknote with a height or "belly" that maintains the overall thickness of the polymer banknote that matches the parts around the banknote. More specifically, the height or thickness of the lenses in the lens array is equal to or less than the adjacent parts of the banknote made of the thickness of the banknote bed and the thickness of the composite image element (for example, the ink layer(s) presenting a fused image) [23,31].

Ink layers (and/or other materials) on both sides of the substrate are combined with the thickness of the substrate. In other words, the height or belly should be approximately equal to or less than the accumulation of ink and/or other layers of material on the protruding face of the lens array provided by, for example, casting or engraving. This is important because if the height or belly of the lens is greater than the thickness of the adjacent ink and/or other layers of material (for example, the height or belly does not exceed about 20 micrometers in some visualizations), the bulge or the "accumulation" in the lens array or that provided by the excellent optical security assembly will allow the banknotes to work properly on a stack of banknotes, including an ATM or cash dispenser, as well as banknote processing [14].

Printing presses and equipment conversion to the production of polymer banknotes will be difficult. In addition, the inventor realized that to achieve a decent 3D image, which is often used for images for optimal currency security features, at least five pixels are usually required in logical resolution or dots per inch (DPI). It can be carefully printed on polymer banknotes. In addition, this mathematical field of possibilities to achieve the desired image on a polymer banknote for a security feature with a lens or lens array limits having a minimum height or inclination (for example, a height or abdomen in the range of about 1 micron up to about 20 micrometers). More specifically, a device or assembly is provided for use as a banknote that has optical security-based features to limit or even prevent counterfeiting [15]. The device consists of a flat substrate and a flat substrate consisting of a thin layer or transparent polymer sheet such as polypropylene. The device consists of an image stack consisting of at least one layer of ink applied to the first side of the flatbed. In addition, optical security assembly (e.g., optical security-based features) is provided that includes a lens array with a plurality of lenses on the first side of the flatbed [14,15].

The lens array extends to the first side adjacent to the image stack. The optical security assembly consists of an image element on the other side of the flatbed at a location in front of the lens array. In some embodiments, the flatbed has a thickness (e.g., less than 100 micrometers such as 60 to 80 micrometers) and the lenses each have a focal length corresponding to the thickness of the flatbed, and focus on the other side of a portion of the body image element is classified. In this method, the array provides a focus lens on the substrate instead of focusing on a point or location outside the substrate or some distance past the second side of the substrate with some previous polymer banknotes. In many embodiments of the device, the lenses are each less than the thickness of the image stack on the first side of the flatbed, and the height may be, for example, in the range of 12 to 18 micrometers less than about 20 micrometers (with an embodiment using a height or belly of 12.5 micrometers). In some cases, the lenses may each have a chord width of fewer than 70 micrometers (for example, such as 55 to 65 micrometers with a specific implementation of having a chord width of 61 micrometers). The lens may be a round lens, a square lens, a hexagonal lens, an elliptical lens, and a lenticules (or a linear lens with a circular, oval, or other cross-section) [29].

To test the device (or polymer banknote), the lens may come in the form of a plurality of lenticules presented in a field in the range of 380–2560 lenses per inch (LPI) (with a 419 LPI used in one run). Additionally, in some visualizations, the image element may contain a plurality of pixels, and each lens is configured to focus on at least five pixels (for example, to present a 3D image or animation). The lens array may include a gap or gap between any adjacent pair of lenses, and the width (or size) of the gap is large enough to provide a relative focus of less than one-fifth the width of the lens. In some specific implementations of the device, the lenses are made of a transparent polymer of the same substrate (e.g., cast on the first side or extruded with the substrate on the first side), and the transparent polymer may have an index failure in the range of 1.4–1.7 (such as 1.47 with a transparent polymer considering the shape of polypropylene (e.g., BOPP, blown propylene film (or "blown film" as it is sometimes called in the industry), or other polymers [28].

In summary, the present description is directed to the polymer banknote, which is designed to include an optical security feature or assembly designed to provide a "focusing bed". For this purpose, the optical security assembly consists of an array of lenses on one side or on a layer of banknotes that are specially configured so that each lens, when bedded with a transparent combination (e.g., transparent, translucent, and clear), the body of the banknote is the focus light passing through the lens on the second or opposite side, or the surface of the transparent bed or the body. In the following description, polymer banknotes that include optical security kits for the first time in a more general way and specific techniques subsequently for the implementation of optical security assemblies with a focused platform are discussed in detail. The 100 banknote is a "polymer" that consists of a body or base of 110 made of clear or polymer plastic but is not limited to polypropylene such as BOPP [27,28].

In terms of security, it should be considered that the biggest forger of plastic banknotes caused a total damage of over RON 1.7 million (EUR 354,000) which is not a big amount. In addition, a fingerprint helped Romanian prosecutors identify the world's biggest forger of plastic banknotes which is one of the security positive points of polymer banknotes [32].

6.2. Benefits of Using Sensors and Optical Membranes

The field of thinking about the production of polymer banknotes and the use of alternative plastics mentioned in the abstract was first developed in 1968 by Australian scientists and scientific organizations. Yet due to a lack of printer facilities and a lack of knowledge of multidimensional materials and thin film polymers, the process of mass production and distribution of polymer banknotes was delayed until 1996 [4,9]. In 1996, in a limited way, and 1998, Australians first saw the use of polymer or plastic instead of cotton, linen, or wood pulp, much to the surprise of many. Yet the main reason why the Reserve Bank of Australia and the scientific organizations of Britain and Australia invested in this banknote model was to prevent widespread counterfeiting of banknotes and damage to nature by using wood paste in ordinary banknotes [4,26].

In the fight against counterfeiting and increasing the security factor, it should be noted that the production materials and raw materials of ordinary banknotes are available to everyone and there is no warning or authentication, and in many cases, even banknote production machines in some countries. It is available to everyone with a weak economy, and even items such as embossed light strips or authentication with basic warning signs have not prevented the counterfeiting of ordinary banknotes [4,26]. Optical transparency and the very high-security factor of polymer banknotes are due to the materials used in these banknotes and the presence of security sensors and optical membranes in polymer banknotes [11,16]. Polymer banknotes are very transparent, have anti-counterfeit security properties, and also have fingerprint properties; the transparency of polymer banknotes is one of the most important ways to prevent counterfeiting of this type of polymer banknotes. Some of the optical properties of Polymer banknotes can be observed in Figure 7.

6.3. Authentication and Security Warning Signs

The three important security issues in polymer banknotes are water marks, metallized plastic yarn, and printing and optical membrane of 3D polymer thin films. The usage of engineered polymeric materials with unique physical and mechanical properties, which will be introduced below, must also be acknowledged because the old banknotes used synthetic and parallel fibers that do not have any complex structure. It is not easy to print a large number of banknotes in many cases due to the complex structure. In selecting and designing the security features of polymer banknotes, the use of membrane lasers by the Delaure company and transparent polymer films have been used by the Innoviafilms company. A schematic of polymer banknote production is shown in Figure 8.

Increasing security factors, polymer banknotes' resistance to rotating damage from optical and variable inks, as well as a transparent layer of a polymer film with an emphasis on 3D materials, have increased the security factor and also prevented counterfeiting of banknotes in circulation [30,31].

Figure 7. Optical properties of polymer banknotes.

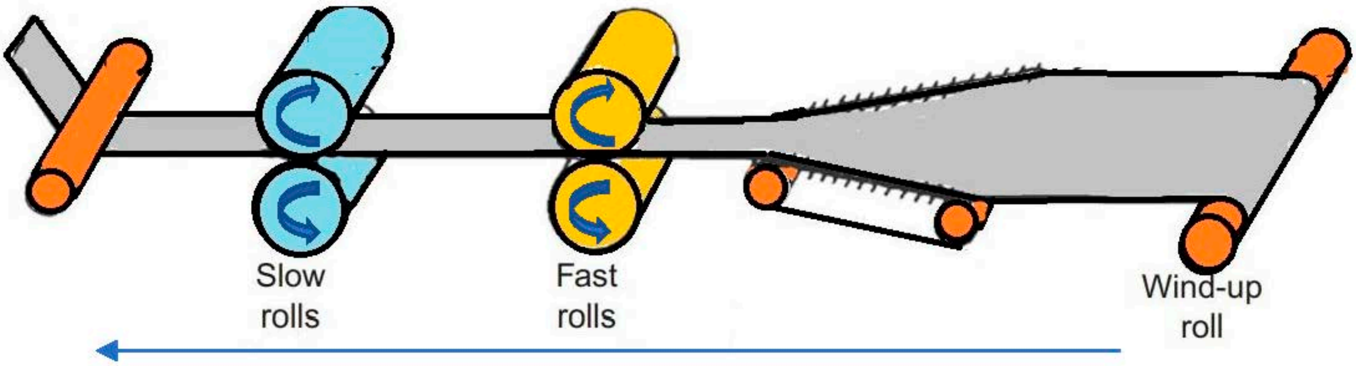

Figure 8. BOPP processing using in Polymer banknote production by the Innoviafilms company.

6.4. Membrane Lasers

Membrane lasers are a particularly important security feature inside polymer banknotes as having two important levers increases security cases and anti-counterfeiting sensors, which are the ability to transfer membrane lasers and change color and ink. It can also change mechanical flexibility.

Nada et al. said that these two factors increase security labels such as the product originality barcode as well as the flexibility and transparency inside the ingredients of polymer banknotes. Membrane lasers can increase the threshold of ingredients and security factors, and significantly reduce counterfeiting of banknote films significantly and sometimes to zero.

For example, the statistics of the University of Oxford, England, and the Reserve Bank, Australia, from 2005 to 2020, illustrate that the trend of counterfeiting in Australia has decreased significantly [23,25,30,33,34].

7. Effects of Polymer Banknotes

7.1. Environmental Effects

Since the beginning of the 21st century, due to the environmental effects of industries such as environmental degradation as well as rising greenhouse gases and global warming, which directly threaten the lives of humans and animals, using Eco-friendly technologies increased day by day. It has led environmentalists and nature lovers to seek to reduce the use of natural resources, as well as the pollution of industries that continuously reduce life expectancy and cause the destruction of natural resources [5,14,17].

In the discussion of paper banknotes that have been in the production, circulation, and use cycle for many years, it should be noted that the main ingredients of paper banknotes are derived from wood pulp, cotton, and linen fibers. Extracted from nature, the printing and ink of paper banknotes is also artificial and does not use lasers and optical membranes, so it cannot be reused or recycled and turned into other materials [1–3]. Due to the very high resistance and refractive index of paper banknotes, it can be concluded that the production of paper banknotes whose production sources are extracted directly from nature has caused irreparable damage to the environment and nature around us [10]. Given that environmental activists, especially in continental Europe emphasize the use of clean resources and environmental degradation, it should be noted that the use of polymer banknotes is much more economical than the use of paper banknotes for the following reasons: (1) damage as it does much less damage to nature and the planet, (2) the use of green materials, and (3) the emphasis on environmental protection that leads to a healthier life and reduces pollution on Earth [10].

Polymer banknotes, due to the nature of their ingredients, which are fully explained in Part 2, are made of engineered polymer films and recyclable composites that have very high transparency. Since they do not absorb dirt, the environment and humans do not transmit pollution. Polymer banknotes do not use synthetic fibers, wood, and paper paste or cotton and synthetic ink; therefore, no material is extracted from nature to produce these banknotes despite the higher cost of producing polymer banknotes than paper banknotes. However, due to the longer life of these banknotes and the lack of environmental degradation, the benefits of using plastic banknotes are much greater than ordinary banknotes [3,9].

The approval of international standard organizations and scientific and industrial unions for polymer banknotes confirms that the use of polymer banknotes in any way will lead to less pollution for humans and also much less control over the use of environmental resources. Thus, it is necessary for environmentalists to constantly remind people all over the world of the benefits of this model of banknote. In the second part, which discussed the comparison of the ingredients of polymer and paper banknotes, we mentioned that the life and circulation cycle of polymer banknotes are much longer, and due to the waterproof and heat-resistant properties of these banknotes, even if damaged or at the end-of-life, can be converted to other materials. For example, polymer banknotes can be used to produce plant pots or plastic cartons, but paper banknotes cannot be recycled and deformed to produce other materials. As a result, polymer banknotes significantly reduce global warming.

Human toxicity (HT, omission of 1,4-DCB to urban air), Fossil fuel depletion (FD, amount of fuels which have been used to produce banknotes), Mineral resource depletion (MRD, emission of Fe), photochemical oxidant formation (POF, amount of emission of NO_x, SO_x, NH_3), Climate change (CC, omission of CO_2), Ozone depletion (OD, amount of registered CFC), terrestrial acidification (TA, omission of SO_2 to air), fresh water eutrophication (FE, emission of P to freshwater), terrestrial ecotoxicity (TET, 1,4-DCB to industrial soil), agricultural land occupation (ALO, the area that the agricultural resources should be consumed to produce banknotes), and water quality were the impact categories that were evaluated. The results could be observed in Figure 9.

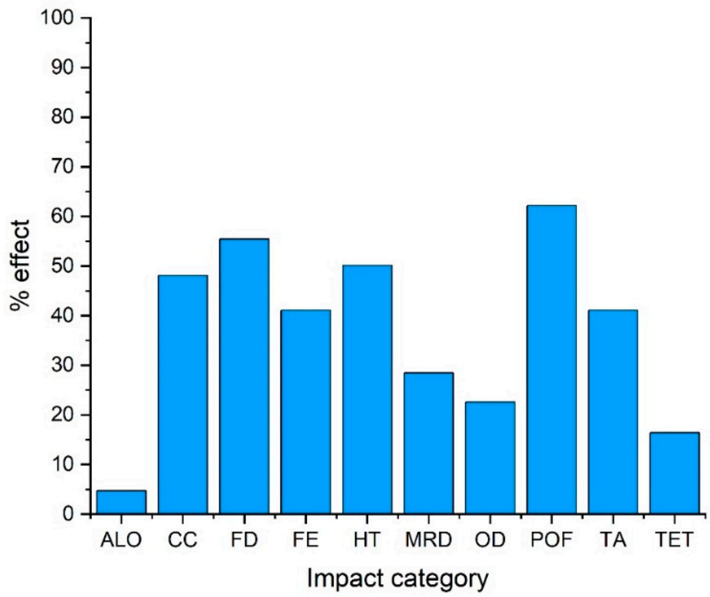

Figure 9. Environmental effect of polymer banknotes compared to paper banknotes.

The outcomes show which factors most significantly influence the effect categories examined. In every category examined, polymer-printed banknotes outperform HD paper-printed banknotes in environmental performance. The category of photochemical oxidant generation has the slightest variation across the analyzed systems, whereas the category of water depletion has the most significant difference. Therefore, it can be said that using polymers in the production of banknotes represents a decrease in both environmental pollution emissions and the depletion of natural resources [33,35].

Low density, chemical and thermal resilience, rigidity, and low cost are a few characteristics of polypropylene that make it a fantastic material for food packaging, particularly microwave-safe containers. Due to the same characteristics, PP has proven to be a wise choice in some industrial and automotive settings. The production of carpets, ropes, automobile components, vehicle batteries, containers, crates, pipelines, furniture, consumer electronics, bottle caps, living hinges, laboratory equipment, storage boxes, buckets, pharmaceutical packaging, and even banknotes all utilize it [36].

PP products that have been recycled may be identical to the originals (such as vehicle components, pallets, and storage bins) or modified for uses requiring less demanding performance standards (such as bike racks, brooms, ice scrapers, buckets, and consumer goods). For instance, after being taken out of circulation, PP banknotes are pulverized and used in industrial and home items such as wheelbarrows, compost bins, and plumbing fittings. Given the strict quality requirements that recycled plastics must achieve to meet regulatory regulations, recycling food containers into food-contact-grade packaging has not yet been achievable; nonetheless, significant efforts are currently being made in the United Kingdom [36].

7.2. Effect on Customer Behaviour

The current study has demonstrated that polymer banknotes will have an impact on both consumer behavior, such as intent to buy or impulsive behavior behind the payment, and the parallel economy of regions of the world, which is the economy that is not included in the state's national income and is not managed by the state. This economy includes straightforward handicrafts and handmade products, individual self-employment, and small-scale manufacturing [34,37,38]. Because the state cannot monitor the flow of currencies and the reasons behind why those who earn money unconnected to the state or its taxes accept them, the polymer currency will affect this kind of economy [37,39–41].

8. Comparison between Paper-Based Banknotes and Polymer Banknotes Properties

In this section, we study the differences between polymer banknotes and paper banknotes regarding mechanical, physical, and durability differences.

8.1. Ageing Effect on Mechanical and Thermal Behaviour

Firstly, the synthetic polymer sheets are thermally treated at a temperature of 50 °C. Then, the impact of thermal treatment on the physical and mechanical characteristics of the banknote sheet was examined. In the next stage, raising the temperature to 160 °C, the mechanical characteristics were examined and the results can be observed in Figures 10 and 11 [33].

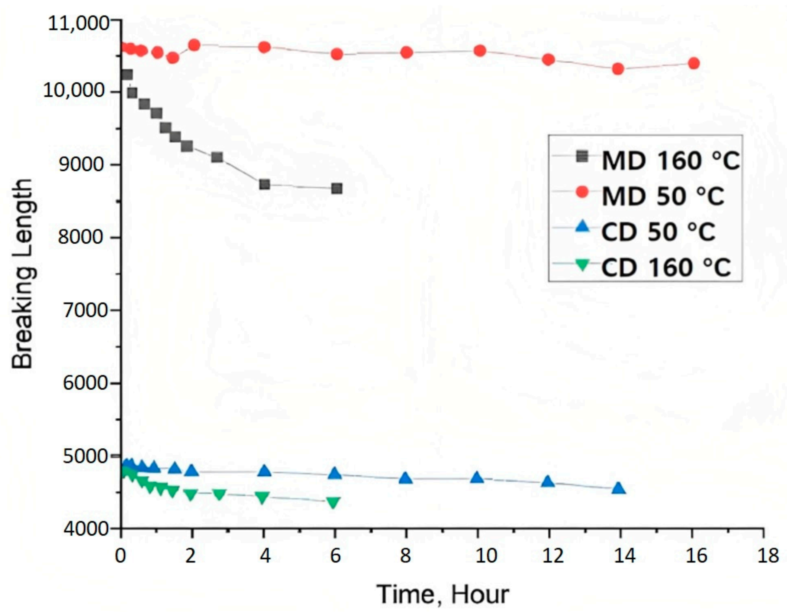

Figure 10. Effect of ageing and temperature on the breaking length of the paper banknote in the machine direction (MD) and cross direction (CD).

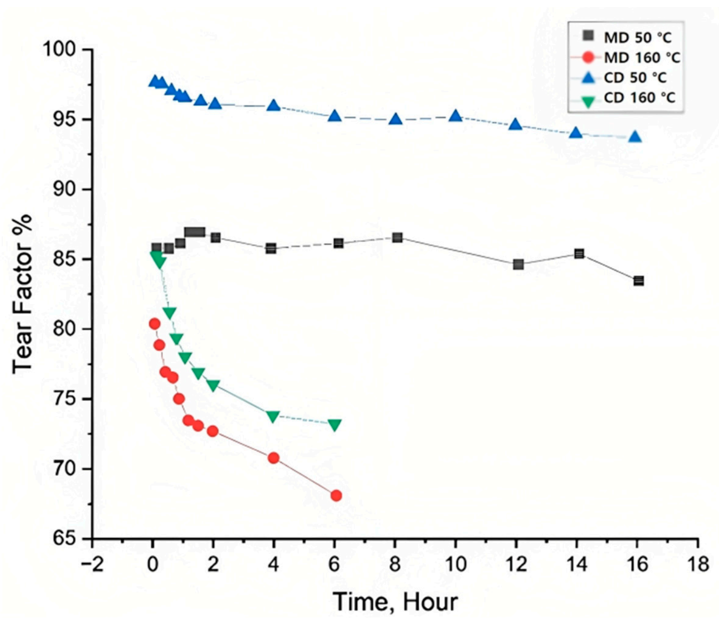

Figure 11. Effect of ageing and temperature on the tear factor of the paper banknote.

8.2. Breaking Length as a Mechanical Behaviour

Ageing causes a more significant reduction in breaking length in the machine direction (MD) than in the cross direction (CD). Synthetic film banknote sheets have longer breaking lengths and more excellent burst factors than paper banknote sheets. In Figure 10, it is shown that the breaking length is much higher in Machine Direction and with increasing temperature, breaking length decreases. However, this decrease is more significant in the machine direction. This diagram was regenerated based on information of research by Nada et al. and the unit of breaking length was not mentioned [33].

8.3. Tear Factor as a Mechanical Behaviour

The total number of fibers involved in the sheet rapture, the length of the fibers, and the quantity and strength of the fiber-to-fiber connections all affect the resistance to tearing. Age does not affect the former. Ageing's impact on the tear factor at cross and machine directions is seen in Figure 11. It is evident from Figure 11 that ageing has a minimal impact on the tear factor at low temperatures, which is to say that it marginally reduces with time at 160 °C. The paper banknote sheet's rip factor significantly decreases when temperatures rise beyond 120 °C. This is also visible while looking across [33].

8.4. Thermal Stability of Paper and Synthesis Polymer Banknotes

Another technique for contrasting sheets of polymeric banknotes is made of paper and synthetic materials. To demonstrate the differences in their thermal behavior, the thermal characteristics of the two types of sheets were examined.

The maximum temperature tolerance of polymer banknotes and paper banknotes is also an essential factor in more use and more resistance of banknotes. Therefore, based on the Thermal Gravimetry Analysis (TGA), the activation energy of polymer banknotes is much higher, and this causes paper banknotes in temperatures 75 to 80 °C to change their structure and physical properties and cause deformation and destruction of the paper banknote. There is a possibility of losing water content in this temperature range and all the physical and mechanical properties could be changed because of that. Yet in the case of polymer banknotes at a temperature of 157 to 165 °C, it changes the properties and shape of the banknote. TGA results indicate that the physical properties and failure time of polymer banknotes are much longer than paper banknotes. It implies the durability and longer life of banknotes, which reduces environmental damage and saves costs in different countries. Paper banknotes use wood, cotton, and textile fibers extensively, which in turn increases the use of natural resources and degrades the environment because there are no alternative resources [10,17].

This weight loss was attributed to the actual pyrolysis by a minor decomposition reaction table after the initial weight loss at 100–120 °C from paper and polymeric sheets decreased. These temperatures were 310 °C and 285 °C for the synthetic and paper banknotes, respectively. In the case of paper sheets, the weight loss percentage is higher than that of synthetic film at this temperature. For biological and polymeric sheets, the primary decomposition temperature was 420 °C. In the case of synthetic polymer sheets, the weight loss was lower than that at the significant decomposition temperature. The weight loss percentage of a paper sheet is the same as that of synthetic polymers when the decomposition temperature is much lower than the paper, as shown in Figure 12.

8.5. Trace Evidence Dynamics of Cocaine

It is commonly known that a significant amount of paper currency in use contains traces of cocaine. One helpful piece of information that can help an investigation is distinguishing between the peaceful transfer of illicit drug particles gained via regular contact with surfaces such as banknotes and transfers arising from criminal activity.

Cocaine is easily transferred from paper and polymer banknotes through contact and transferred more readily from polymer banknotes. It is more easily lost from polymer banknotes after handling, while it persists on both banknote types after extensive handling. It was transferred more readily from contacts involving rotation than contacts not involving rotation. Cocaine particles were transmitted from polymer banknotes more frequently than from paper banknotes. This is probably brought on by variations in surface topography

(Figure 13). The findings imply that cocaine particles are less likely to be kept on non-porous polymer banknotes and are more likely to be maintained within the porous matrix of paper banknotes. This outcome was anticipated and is consistent with prior research that evaluated how surface type affects the transmission of trace forensic materials such as DNA [38].

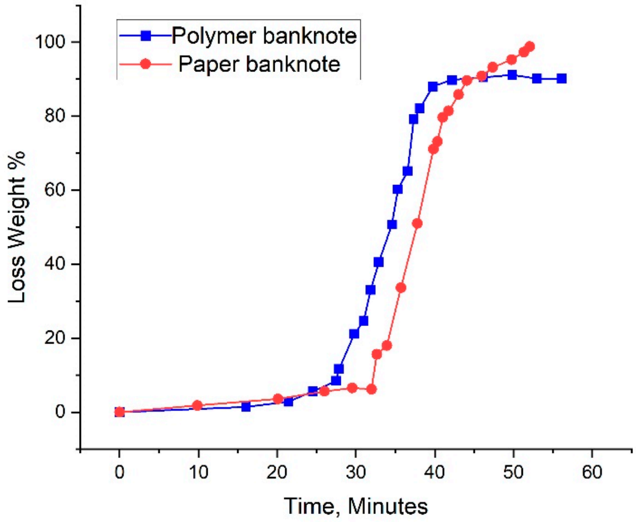

Figure 12. TGA curves of paper banknote sheet and synthetic polymer banknote.

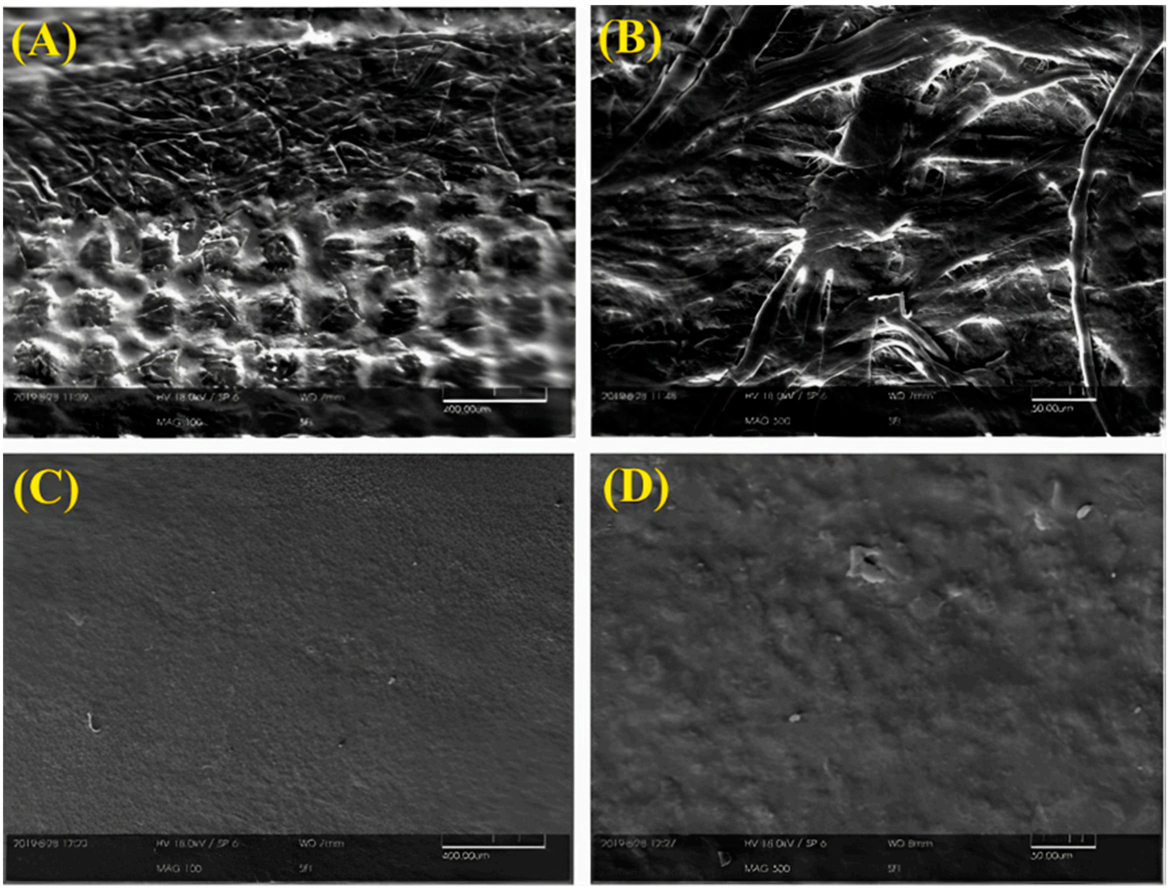

Figure 13. SEM micrographs of the US one-dollar paper banknote: (**A**) 100× magnification and (**B**) 1000× magnification. Vietnamese twenty-thousand dong polymer banknote: (**C**) 100× magnification and (**D**) 1000× magnification [38].

9. Conclusions

Using Polymer banknotes is becoming more and more popular in different countries due to their excellent properties, durability, and environmentally friendly features. Polymer banknotes have 50% less destructive effects on the environment. Paper banknotes' tear factor is more elevated than polymer banknotes. Practically, the mechanical properties of the polymer banknotes are measured after warming up the temperature 120–200 °C for various time intervals. In contrast, the mechanical properties of the paper banknotes are highly affected after heating at 80 °C and provide unacceptable results. Polymer banknotes consistently have better thermal treatment resistance than paper banknotes, especially at high temperatures. Due to the structure of composite materials and nano-materials in their fiber network, polymer banknotes have a very high factor in countering banknote counterfeiting. Paper banknotes have more roughness on their surface in comparison to polymer banknotes and for this reason, they cause more pollution for humans and the environment. In the end, using polymer banknotes instead of paper banknotes could be an effective way to help the economy and the environment, and could become an introduction to more use of green energies around the world.

10. Suggestions

According to the context, there is a worldwide willingness to change paper banknotes to polymer banknotes, due to their environmental effects and better properties. However, there are few articles specifically about the mechanical and physical properties of polymer banknotes and paper banknotes. The authors strongly recommend, for a comprehensive study, to compare different types of banknotes in different aspects. In addition, during the revision process, a question was raised by one of the reviewers, which could be a study case in itself. The question is, if there are a lot of positive points in polymer banknotes in different aspects such as sustainability, properties, security, and economy, why are so many of the worldwide currencies still produced by paper and so many developed countries still using paper banknotes. Consequently, the authors would suggest conducting a deeper comprehensive review activity in this area once more details become available.

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References

1. Solomon, D.; Spurling, T. *The Plastic Banknote: From Concept to Reality*; CSIRO Publishing: Melbourne, VIC, Australia, 2014. Available online https://www.publish.csiro.au/book/6490 (accessed on 7 February 2023).
2. Rogers, J.A.; Someya, T.; Huang, Y. Materials and Mechanics for Stretchable Electronics. *Science* **2010**, *327*, 1603–1607. [CrossRef] [PubMed]
3. Available online: https://www.royaldutchkusters.com/blog/the-five-pros-and-cons-of-polymer-banknotes (accessed on 8 February 2023).
4. Available online: https://www.rbnz.govt.nz/money-and-cash/banknotes/the-history-of-banknotes-in-new-zealand (accessed on 7 February 2023).
5. Wilson, G.J. Australian polymer banknote: A review, Optical Security and Counterfeit Deterrence Techniques II. In Proceedings of the PHOTONICS WEST '98 ELECTRONIC IMAGING, San Jose, CA, USA, 24–30 January 1998. [CrossRef]

6. Romanic, H.; Jackson, W.K. Australian Patent PCT/AU00/00629, 2000. Intaglio Contrast Effect The Intaglio Contrast Effect Works by Printing an Intaglio Design on Top of a Highly Reflective Metallic Patch. When the Intaglio Design Is Viewed at Different Angles the Colour Becomes Brighter and More enhancedwo2000076784a1—Security Document or Device Having an Intaglio Contrast Effect, Google Patents. Google. 2000. Available online: https://patents.google.com/patent/WO2000076784A1/en (accessed on 7 February 2023).
7. Available online: https://en.wikipedia.org/wiki/Polymer_banknote (accessed on 7 February 2023).
8. Spencer, C. Paying with Polymer: Developing Canada's New Bank Notes, Bank of Canada Review, Spring. 2011, pp. 37–45. Available online: https://www.bankofcanada.ca/wp-content/uploads/2011/06/spencer.pdf (accessed on 7 February 2023).
9. Han, T.-H.; Lee, Y.; Choi, M.-R.; Woo, S.; Bae, S.-H.; Hong, B.H.; Ahn, J.-H.; Lee, T.-W. Extremely efficient flexible organic light-emitting diodes with modified graphene anode. *Nat. Photon* **2012**, *6*, 105–110. [CrossRef]
10. White, M.S.; Kaltenbrunner, M.; Głowacki, E.D.; Gutnichenko, K.; Kettlgruber, G.; Graz, I.; Aazou, S.; Ulbricht, C.; Egbe, D.A.M.; Miron, M.C.; et al. Ultrathin, highly flexible and stretchable PLEDs. *Nat. Photon* **2013**, *7*, 811–816. [CrossRef]
11. Kaltenbrunner, M.; Sekitani, T.; Reeder, J.; Yokota, T.; Kuribara, K.; Tokuhara, T.; Drack, M.; Schwödiauer, R.; Graz, I.; Bauer-Gogonea, S.; et al. An ultra-lightweight design for imperceptible plastic electronics. *Nature* **2013**, *499*, 458–463. [CrossRef]
12. International Monetary Fund Bosnia and Herzegovina: Financial Sector Assessment Program-Detailed Assessment of Observance of the CPMI-IOSCO Principles for Financial Market Infrastructures. *IMF Staff. Ctry. Rep.* **2015**, *15*, 1. [CrossRef]
13. Xia, R.; Heliotis, G.; Bradley, D.D.C. Fluorene-based polymer gain media for solid-state laser emission across the full visible spectrum. *Appl. Phys. Lett.* **2003**, *82*, 3599–3601. [CrossRef]
14. Available online: https://www.imf.org/external/pubs/ft/fandd/2016/06/pdf/currency.pdf (accessed on 7 February 2023).
15. Hardwick, B.; Jackson, W.; Wilson, G.; Mau, A.W.H. Advanced Materials for Banknote Applications. *Adv. Mater.* **2001**, *13*, 980–984. [CrossRef]
16. Bengiat, R.; Liptz, Y.; Rajs, N.; Bentolila, A.; Levin-Elad, M. Time is Money or Money is Time? A Rapid Operational Sequence for Detecting Fingermarks on Polymer Banknotes. *J. Forensic Sci.* **2020**, *65*, 1465–1473. [CrossRef]
17. Vásquez-Garay, F.; Carrillo-Varela, I.; Vidal, C.; Reyes-Contreras, P.; Faccini, M.; Mendonça, R.T. A Review on the Lignin Biopolymer and Its Integration in the Elaboration of Sustainable Materials. *Sustainability* **2021**, *13*, 2697. [CrossRef]
18. Jones, N.; Kelly, M.; Stoilovic, M.; Lennard, C.; Roux, C. The development of latent fingerprints on polymer banknotes. *J. Forensic Identif.* **2003**, *53*, 50–77. Available online: https://researchprofiles.canberra.edu.au/en/publications/the-development-of-latent-fingerprints-on-polymer-banknotes (accessed on 7 February 2023).
19. Marabello, D.; Benzi, P.; Lombardozzi, A.; Strano, M. X-ray Powder Diffraction for Characterization of Raw Materials in Banknotes. *J. Forensic Sci.* **2017**, *62*, 962–970. [CrossRef] [PubMed]
20. McClintock, R.; Whymark, R. Bank of England Notes: The Switch to Polymer, Bank of England Quarterly Bulletin, Q 1. 2016, pp. 23–32. Available online: https://www.bankofengland.co.uk/-/media/boe/files/quarterly-bulletin/2016/boe-notes-the-switch-to-polymer.pdf?la=enandhash=9F33836E77E82605F6CAF7E928E0BDBD70B734C3 (accessed on 7 February 2023).
21. Scotcher, K.; Bradshaw, R. The analysis of latent fingermarks on polymer banknotes using MALDI-MS. *Sci. Rep.* **2018**, *8*, 1–13. [CrossRef] [PubMed]
22. International Monetary Fund Report to the Executive Boards of the IMF and the World Bank on the New CPSS-IOSCO Principles for Financial Market Infrastructures. *Policy Pap.* **2012**, *2012*. [CrossRef]
23. Karnutsch, C.; Pflumm, C.; Heliotis, G.; Demello, J.C.; Bradley, D.D.C.; Wang, J.; Weimann, T.; Haug, V.; Gartner, C.A.; Lemmer, U. Improved organic semiconductor lasers based on a mixed-order distributed feedback resonator design. *Appl. Phys. Lett.* **2007**, *90*, 131104. [CrossRef]
24. Chen, Y.; Herrnsdorf, J.; Guilhabert, B.J.E.; Kanibolotsky, A.L.; Mackintosh, A.R.; Wang, Y.; Pethrick, R.A.; Gu, E.; Turnbull, G.A.; Skabara, P.J.; et al. Laser action in a surface-structured free-standing membrane based on a π-conjugated polymer-composite. *Org. Electron.* **2011**, *12*, 62–69. [CrossRef]
25. Reserve Bank of New Zealand: Bulletin. Available online: https://www.rbnz.govt.nz/money-and-cash/banknotes (accessed on 7 February 2023).
26. Available online: https://www.rbnz.govt.nz/hub/-/media/project/sites/rbnz/files/publications/bulletins/2014/2014dec77-7.pdf?sc_lang=en (accessed on 7 February 2023).
27. Karl, M.; Whitworth, G.L.; Schubert, M.; Dietrich, C.P.; Samuel, I.D.W.; Turnbull, G.A.; Gather, M.C. Optofluidic distributed feedback lasers with evanescent pumping: Reduced threshold and angular dispersion analysis. *Appl. Phys. Lett.* **2016**, *108*, 261101. [CrossRef]
28. Finger, N.; Schrenk, W.; Gornik, E. Analysis of TM-polarized DFB laser structures with metal surface gratings. *IEEE J. Quantum Electron.* **2000**, *36*, 780–786. [CrossRef]
29. Amarasinghe, D.; Ruseckas, A.; Vasdekis, A.E.; Turnbull, G.A.; Samuel, I.D.W. High-Gain Broadband Solid-State Optical Amplifier using a Semiconducting Copolymer. *Adv. Mater.* **2009**, *21*, 107–110. [CrossRef]
30. Singh, N. Polymer Banknotes—A Viable Alternative to Paper Banknotes. *Asia Pac. Bus. Rev.* **2008**, *4*, 42–50. [CrossRef]
31. Delori, F.C.; Webb, R.H.; Sliney, D.H. Maximum permissible exposures for ocular safety (ANSI 2000), with emphasis on ophthalmic devices. *J. Opt. Soc. Am. A* **2007**, *24*, 1250–1265. [CrossRef]
32. Available online: https://www.romania-insider.com/fingerprint-biggest-forger-plastic-banknotes (accessed on 7 February 2023).

33. Nada, A.M.A.; El-Kady, A.; Simonian, M.; Basalah, G.; Ahmed Goher, R. Thermal Behavior of Natural and Synthetic Polymer Banknotes. First Arab International Conference of Forensic Science and Forensic Medicine. *Arab J. Forensic Sci. Forensic Med.* **2015**, *1*, 143–148.
34. Karl, M.; Glackin, J.M.E.; Schubert, M.; Kronenberg, N.M.; Turnbull, G.A.; Samuel, I.D.W.; Gather, M.C. Flexible and ultra-lightweight polymer membrane lasers. *Nat. Commun.* **2018**, *9*, 1525. [CrossRef] [PubMed]
35. Luján-Ornelas, C.; Sternenfels, U.M.D.C.; Güereca, L.P. Life cycle assessment of Mexican polymer and high-durability cotton paper banknotes. *Sci. Total Environ.* **2018**, *630*, 409–421. [CrossRef] [PubMed]
36. Xanthos, M. Recycling of the #5 Polymer. *Science* **2012**, *337*, 700–702. [CrossRef]
37. Orabi, M.M.A. Would Polymer Banknotes (Plastic Money) Influence Customer Intention to Buy? An Empirical Study from Jordan. *J. Asian Financ. Econ. Bus.* **2022**, *9*, 355–361. [CrossRef]
38. Amaral, M.; Gibson, A.; Morgan, R. Trace evidence dynamics of cocaine on banknotes: A comparison study of paper and polymer banknotes. *Sci. Justice* **2022**, *62*, 221–228. [CrossRef]
39. Tran, T.K.P. Unemployment and Shadow Economy in ASEAN Countries. *J. Asian Financ. Econ. Bus.* **2021**, *8*, 41–46. [CrossRef]
40. Luong, T.T.H.; Nguyen, T.M.; Nguyen, T.A.N. Rule of Law, Economic Growth and Shadow Economy in Transition Countries. *J. Asian Financ. Econ. Bus.* **2020**, *7*, 145–154. [CrossRef]
41. Duong, D.V.N.A.M.T.H. Shadow Economy, Corruption and Economic Growth: An Analysis of BRICS Countries. *J. Asian Financ. Econ. Bus.* **2021**, *8*, 665–672. [CrossRef]