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Research on the Performance of Cosmetics Packaging Materials under the Background of Green Transformation

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Abstract: With the acceleration of global green transformation, the cosmetics industry is facing an urgent need for sustainable upgrading of packaging materials. This study focuses on the performance optimization of cosmetic packaging materials, conducting a systematic analysis from three dimensions: material compatibility, harmful substance detection, and biodegradable material development. By constructing a multidimensional compatibility evaluation system, developing trace plasticizer detection technology, and exploring the preparation process of high-performance degradable materials, a comprehensive solution for green packaging materials is ultimately proposed. Experiments have shown that biodegradable materials based on polylactic acid (PLA) and nanocellulose composites have better mechanical strength and degradation efficiency than traditional plastics, and the new detection technology can achieve ppb level detection accuracy for phthalate plasticizers. This study provides theoretical support and technical pathways for the green transformation of cosmetic packaging.

Keywords: Green Transformation; Cosmetics Packaging; Material Compatibility; Degradable Materials; Trace Detection.

1. Introduction

With the continuous expansion of the global cosmetics market, the safety and sustainability of packaging materials have become the focus of industry attention. Traditional plastic packaging such as polyvinylidene chloride (PVDC) faces two core issues: plasticizers such as phthalates (PAEs) may migrate into cosmetics through contact and have endocrine disrupting properties; Every year, 1.2 million tons of cosmetic plastic packaging waste are generated globally, with only 9% being recycled. The development of biodegradable materials is urgently needed. This study aims to address the aforementioned pain points by systematically conducting compatibility testing of packaging materials, precise determination of harmful substances, and research and development of environmentally friendly alternative solutions, providing technical support for the green transformation of the cosmetics industry.

2. Research Contents

2.1. Compatibility Testing of Packaging Materials

2.1.1. Compatibility Testing of Packaging Materials and Cosmetic Contents

The compatibility testing of packaging materials and contents mainly includes physical compatibility, chemical compatibility, and biocompatibility. The physical compatibility test is relatively simple, mainly examining whether the contents and related packaging materials undergo physical changes such as adsorption, permeation, precipitation, cracking, etc. when stored under high temperature, low temperature, and normal temperature conditions. Although packaging materials such as ceramics and plastics usually have good tolerance and stability, there are still phenomena such as adsorption and permeation [1], so it is necessary to investigate the physical compatibility between packaging materials and their contents. Chemical compatibility mainly examines whether the contents and related packaging materials undergo chemical changes during storage at high, low, and normal temperatures, such as discoloration, odor, pH changes, delamination, and other abnormal phenomena. For biocompatibility testing, it mainly refers to the migration of harmful substances from packaging materials to the contents. From a mechanistic analysis, the migration of these toxic and harmful substances is partly due to the presence of concentration gradients, that is, there is a large concentration gradient at the interface between packaging materials and cosmetic contents; On the other hand, it is due to the existence of diffusion behavior, that is, cosmetics may interact with packaging materials, and even enter the interior of packaging materials, leading to the dissolution of harmful substances [2]. Therefore, in the case of long-term contact between packaging materials and cosmetics, toxic and harmful substances in the packaging materials are likely to migrate. For the regulations on heavy metals in packaging materials, GB 9685-2016 Standard for the Use of Additives in Food Contact Materials and Products specifies the migration amounts of heavy metals lead (1 mg/kg), antimony (0.05 mg/kg), zinc (20 mg/kg), and arsenic (1 mg/kg). The detection of cosmetic packaging materials can refer to the regulations in the food industry. The detection of heavy metals usually uses atomic absorption spectroscopy, inductively coupled plasma mass spectrometry, atomic fluorescence spectrophotometry, etc. [3]. Usually, these plasticizers, antioxidants, and other additives have low concentrations, and detection requires extremely low detection or quantification limits (μ g/L or mg/L), which require the use of high-performance liquid chromatography, gas chromatography, gas chromatography-mass spectrometry, etc. [4]. But not all dissolved substances will have a serious impact on cosmetics. As long as the amount of dissolved substances meets relevant national regulations and testing standards, and is harmless to the user, these dissolved substances are considered normal compatibility.

2.1.2. Secondary Processing of Packaging Materials and Compatibility Testing of Contents

The compatibility test between the secondary processing of packaging materials and the contents usually refers to the compatibility between the coloring and printing processes of packaging materials and the contents. The coloring process of packaging materials mainly includes electroplating, spraying, wire drawing, gold and silver coating, secondary oxidation, injection molding, etc. The printing process of packaging materials mainly includes screen printing, hot stamping, water transfer printing, heat transfer printing, offset printing, etc. This type of compatibility testing usually refers to coating the surface of packaging materials with contents, and then subjecting the sample to long-term or short-term compatibility experiments under high temperature, low temperature, and room temperature conditions. The main testing indicators are whether the appearance of the packaging material has cracks, deformations, fading, and other phenomena. In addition, due to the presence of some harmful substances to human health in ink, the migration of ink into the internal contents of the packaging material during secondary processing should also be investigated.

2.2. Harmful Substance Detection and Analysis

Cut the sample of polyvinylidene chloride (PVDC) cosmetic packaging to be tested into square sample pieces with a size of 2 mm ×2 mm, and then preprocess the sample pieces. Grind the liquid nitrogen treated sample into powder, take out 2 g of the sample and place it in a Soxhlet extractor. Add 40 mL of trichloroethane to the extractor, set the extraction temperature to 65 ℃, and extract for 5 hours. Filter and concentrate the extracted liquid, then add acetonitrile to a volume of 5 mL [5-6]. Then, perform gradient elution on the solution after reaching a constant volume, with an initial temperature of 70 ℃, and raise the temperature to 80 ℃ for 4.5 minutes; Heat up to 90 ℃ in 4.8 minutes; Heat up to 90 ℃ within 10 minutes; Heat up to 95 ℃ within 15 minutes; Then gradually cool down, and cool down to 70 ℃ within 30 minutes [7-8]. Then filter the obtained solution into a colorimetric tube, mix well, and take the upper extraction solution for mass spectrometry analysis.

2.3. Development of Biodegradable Materials

In the development and research of biodegradable materials, based on polylactic acid, a new environmental protection system is constructed by composite modification of natural polymer materials, with a focus on optimizing material processing technology and interface compatibility, aiming to solve the problems of insufficient mechanical properties, high production costs, and limited scale production of traditional biodegradable materials. The study adopts melt blending and continuous production technology, and significantly improves the mechanical strength and barrier properties of materials by adjusting processing parameters and filler ratios, while reducing production costs. By combining the full lifecycle assessment method, the environmental friendliness of the material is systematically verified, revealing its potential in reducing carbon emissions and waste pollution, providing a functional, economical, and ecologically sustainable alternative solution for the cosmetics packaging industry.

3. Key Technology

3.1. Multidimensional Compatibility Evaluation System for Key Technologies

Build a multi-level collaborative evaluation model of "physics chemistry function", systematically integrating the three dimensions of interface interaction between packaging materials and cosmetic ingredients, long-term storage stability, and functional impact. By designing accelerated aging experiments to simulate real storage environments, the correlation mechanism between material deformation, transmittance changes, and content oxidation stability is revealed, and a comprehensive compatibility evaluation index system based on principal component analysis (PCA) is established. Propose a "dynamic tracking threshold warning" evaluation method, combined with machine learning algorithms to predict the compatibility risk level of packaging materials in different formulation systems, providing material selection decision support for cosmetics enterprises. Develop standardized test process, cover different dosage forms such as lotion, cream and essential oil, clarify quantitative evaluation standards for key issues such as material swelling and active ingredient adsorption, and fill the technical gap in the industry's full cycle performance evaluation of packaging materials.

3.2. Trace Plasticizer Detection Technology

Develop a high-sensitivity plasticizer detection platform based on gas chromatography-mass spectrometry (GC-MS/MS) and establish a trace migration analysis method for six phthalates (PAEs) in cosmetic packaging. Optimize QuEChERS pretreatment technology and achieve efficient purification of complex matrix interference through adsorbent combination screening (PSA+C18), raising the detection limit to the 0.001 mg/kg level. Construct a migration dynamics model to analyze the nonlinear effects of temperature, contact time, and lipid solubility on the migration rate of PAEs, and propose a three-stage theoretical framework of "migration path diffusion coefficient distribution equilibrium". Develop a standardized testing process for multi-component harmful substances in cosmetics contact materials, covering the entire process of sample preparation, instrument parameter optimization, and data validation.

3.3. Preparation of High-Performance Degradable Materials

Develop an interface compatibilization and functional modification process for polylactic acid (PLA) - based composite materials, revealing the "rigidity toughness" balance mechanism of the synergistic enhancement of material mechanical properties by modified starch (MS) and nanocellulose (CNF). Developing continuous production technology for twin-screw extrusion, breaking through the technical bottleneck of uneven dispersion of natural fillers through temperature gradient control of melt blending (170-185 ℃) and optimization of screw shear force, and achieving synchronous improvement of tensile strength and barrier performance of composite materials. Propose an integrated control strategy of "process structure performance", integrate melt flow index (MFI) monitoring and microstructure characterization (SEM), and establish a database of degradable material processing parameters. Build a low-cost production plan, optimize the proportion of fillers and control energy consumption to reduce the overall material cost by more than 30% compared to traditional PLA. Combining life cycle assessment (LCA) to quantify the carbon emissions and resource consumption of materials from raw material extraction to waste disposal, providing a functional and ecologically sustainable alternative solution for the industry's green transformation.

4. Experimental Result

4.1. Compatibility Evaluation of Packaging Materials

The compatibility between packaging materials and cosmetic contents is significantly influenced by the storage environment and the physical and chemical properties of the materials themselves. In physical compatibility testing, some plastic packaging showed slight deformation and decreased light transmittance under high temperature (45℃) conditions, while ceramic materials did not crack or adsorb in low temperature (-20℃) environments. However, high fat soluble cosmetics (such as essential oils) showed a clear tendency to penetrate when in contact with plastics. Chemical compatibility analysis shows that after long-term storage, some packaging materials undergo oxidation reactions at the interface with the contents, resulting in a pH shift (±0.3~0.5) and a decrease in the retention rate of active ingredients (such as a maximum degradation rate of 18% for vitamin C) in cosmetics. In biocompatibility testing, the migration of PAEs in PVDC packaging showed a trend of rapid increase followed by gradual flattening during the simulated shelf life, and the migration risk was positively correlated with the lipid solubility of cosmetics. In addition, the ink migration test of the secondary processing technology found that the metal coating of the hot stamping process partially peeled off at high temperatures, while trace amounts of benzene based compounds were detected migrating in the silk screen ink. Further optimization of the processing technology is needed to avoid safety risks.

4.2. Harmful Substance Detection and Analysis

Based on optimized GC-MS/MS detection method, precise identification of trace levels of six PAEs in cosmetic packaging has been successfully achieved, with detection sensitivity increased by one order of magnitude compared to traditional methods. The experiment verified the purification efficiency of QuEChERS pretreatment technology for complex matrices (such as oil containing lotion), and effectively eliminated the false positive influence of such interfering substances as pigments, spices, etc. on the test results. The migration kinetics model shows that the migration rate of PAEs increases exponentially in the initial stage (0-30 days), and then enters a slow diffusion period. For every 10 ℃ increase in temperature, the migration rate increases by about 2.3 times. The testing of 20 types of PVDC packaging on the market found that 15% of the samples had DEHP migration levels close to the EU REACH regulation limit (0.1%), with the risk of high transmittance thin-walled packaging being particularly prominent. In addition, heavy metal migration tests have shown that although the lead and arsenic content in all samples meets national standards, there is a potential risk of exceeding the standard for cadmium elements in some colored spray packaging, indicating the need to strengthen the quality control of raw materials in the secondary processing stage.

4.3. Performance Verification of Biodegradable Materials

PLA based composites show excellent rigidity toughness balance in mechanical property test, and their tensile strength and elongation at break are 85% and 120% of those of traditional PVDC materials respectively, and their barrier properties to water vapor and oxygen are more than 40% higher than those of pure PLA, fully meeting the packaging requirements of highly active cosmetics (such as antioxidant essence). The stability test of continuous production process shows that the optimized twin-screw extrusion parameters can ensure the uniformity of filler dispersion (SEM shows that CNF is dispersed at the nanoscale in the matrix), and the performance difference between batches is less than 5%. The results of the Life Cycle Assessment (LCA) show that the carbon emissions of the new material from raw material production to waste disposal are reduced by 41% compared to PVDC, and soil burial experiments have verified that it can complete over 90% biodegradation within 180 days without detecting microplastic residues. In addition, in actual filling tests, the packaging scheme using this material extended the shelf life of sensitive formulas by 15%, and no leakage or structural failure occurred in transportation vibration simulations, verifying its feasibility for industrial application.

5. Conclusion

This study reveals the migration law of PAEs in PVDC packaging, proposes a three factor control strategy of "temperature contact area fat solubility", develops a continuous production process for biodegradable composite materials, reduces costs by 32% compared to traditional PLA, constructs a cosmetic packaging full life cycle assessment database, and provides green material selection decision support for the industry. Experimental data shows that the new packaging scheme can extend product shelf life by 15% and reduce carbon footprint by 41%. This study provides a systematic solution for the collaborative optimization of "safety function environmental protection" in cosmetic packaging, promoting the industry's transformation towards a circular economy model.

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