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Article

Bicycle Lock Analysis: Sustainability and Material Analysis

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Abstract: This paper comprehensively analyzes the structural components and material compositions of bicycle locks to compare conventional models with those manufactured from sustainable and biodegradable materials. As the global demand for eco-friendly transportation accessories increases, understanding the chemical safety and environmental footprint of these products becomes critical. Focusing specifically on the ZOLi 87610 bicycle lock, this study systematically contrasts a standard commercial version with a recycled counterpart produced by the same manufacturing company. A rigorous quantitative experiment was conducted to measure the presence of toxic phthalates within the lock components. This procedure strictly adhered to the established GB/T 29786-2013 testing standard, utilizing advanced Gas Chromatography-Mass Spectrometry (GC-MS) for precise chemical detection. The analytical results reveal a highly significant disparity between the two models: the ordinary lock contained 2,554 mg/kg of diisobutyl phthalate (DIBP), a concentration that significantly exceeds international safety limits, whereas the sustainable lock demonstrated no detectable traces of any toxic substances. Beyond the primary chemical analysis, this paper extensively discusses the broader economic and environmental impacts associated with utilizing recycled plastics in industrial production. The findings note substantial reductions in overall energy consumption, greenhouse gas carbon emissions, and direct manufacturing costs when compared to the processing of virgin materials. Ultimately, the research suggests that sustainable materials can successfully achieve the necessary mechanical durability while simultaneously offering end-of-life biodegradability. The conclusion firmly asserts that adopting recycled materials in the bicycle lock industry effectively mitigates environmental pollution and actively protects human health from harmful endocrine-disrupting chemicals.

Keywords: bicycle lock; phthalates; sustainable materials; recycled plastic; biodegradability

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1. Introduction

Bicycles have long served as one of the most common tools for transportation, maintaining popularity as a primary method for traveling short distances. Consequently, the necessity of protecting these vehicles from theft led to the invention and widespread use of bicycle locks. Traditionally, the industry has prioritized maximum durability and strength, resulting in locks predominantly manufactured from hardened steel. A prime example of this traditional approach is the classic Kryptonite "New York" U-Lock, which utilizes a U-shaped structure built from hardened steel. While this material choice ensures the physical security of the bicycle, the manufacturing process behind it is environmentally costly [1]. The extraction of raw materials, specifically the mining and smelting of raw iron, followed by the melting of different iron types to produce steel, consumes vast amounts of energy and is responsible for significant carbon dioxide emissions.

In recent years, the environmental impact of these manufacturing processes has drawn scrutiny. Countries in North America and Europe have gradually begun to resist the retail and production of traditional bicycle locks that do not meet modern environmental standards. Several years ago, strict laws were implemented in these regions to regulate the permissible amount of chemicals in specific lock components. These regulations have had a significant impact on China's export lock industry, forcing a shift in production methods. To comply with these new standards and reduce the presence of harmful chemicals like phthalates, factories have started producing locks that feature recycled materials and body parts dyed with organic dyes. An example of this industrial shift is the product WL0654 from Sinox Lock. According to their laboratory testing results, this lock uses up to 85% Post-Consumer Recycled (PCR) plastic in its housing while maintaining the same level of durability and resistance as ordinary locks.

This shift highlights that materials are the most critical factor in determining the biodegradability and sustainability of a lock [2]. To understand the material composition of a standard product, this paper analyzes the ZOLi 87610 Easy Installation Bicycle Key Pink Wire Bike Cable Combination Lock, manufactured by the Zhejiang ZOLi Company. As shown in the material percentage data, aluminum constitutes 35% of the lock, followed by plastic/polymers at 20%, rubber at 15%, and other metals (such as tin, copper, and lead) at 20%, with the remaining 10% consisting of other elements or impurities. Steel and plastics are the materials that occupy the largest percentage of the lock's composition.

Steel remains the most important component for protection. However, the industry is moving toward recycled steels, metals removed from other products that are selected for quality, size, and purity before being melted together [3]. Even though recycled steel requires smelting, the energy savings are substantial; the process uses approximately 70% less energy than producing new virgin steel and emits around 58% fewer greenhouse gases. Some manufacturers now offer locks made from 100% recycled steel, proving that strength and sustainability can coexist in a single product.

Similarly, the use of recycled plastic in bicycle locks is a crucial advancement. Currently, most recycled materials used in manufacturing are PET and PC plastics derived from water bottles or other recycled goods. According to Green Matters, using a recycled-plastic chain lock secures the bike while simultaneously preventing landfill waste [2]. This process keeps plastic out of landfills and avoids the production of new polymers. Since manufacturing virgin plastic requires oil extraction from petroleum, refining, and polymerization, all of which generate air pollution and consume energy, the use of recycled plastic effectively avoids an equivalent amount of these environmental costs.

2. Materials and Methods

2.1. Experimental Setup and Materials

The primary objective of this experiment was to measure the quantity of phthalates contained in various bicycle lock components, with a specific focus on parts that users frequently touch or contact in daily life [1]. To ensure industrial compliance, the experiment was conducted in collaboration with a local company in Wenzhou City, which performs these tests to verify if products meet the regulatory limits of importing countries.

The analysis required specific high-purity chemical reagents to ensure accurate extraction and detection [3]. The main chemicals utilized in the process, along with their respective manufacturers, are listed in Table 1.

Table 1. Chemicals Used in the Experiment

Chemicals Used	Production Company
Toluene	Tedia Company, LLC
n-Hexane	Tianjin Siyou Fine Chemicals Co., Ltd.
Anhydrous Ethanol	Shanghai Reagent General Factory Chemical Co., China

Ethyl Acetate	Changshu Hongsheng Fine Chemical Co., Ltd.
Dichloromethane	Guangdong Guanghua Sci-Tech Co., Ltd.
Standard Solution	Shanghai Anpu Cuisis Standard Technical Service Co., Ltd.

A range of precision instruments was employed for sample preparation, extraction, and final analysis [4]. The core analysis was performed using a Gas Chromatograph--Mass Spectrometer (GC-MS), supported by various auxiliary devices detailed in Table 2.

Table 2. Devices and Machines Used

Devices and Machines Used	Production Company
Gas Chromatograph-Mass Spectrometer, QP2010 SE	Shimadzu Corporation (Japan)
Rotary Evaporator, RE-52A	Shanghai Yarong Biochemical Instrument Factory
Circulating Water Vacuum Pump, SHZ-D(III)	Gongyi Yuhua Instrument Co., Ltd
Nitrogen Evaporator, DC-12	Shanghai Anpu Scientific Instrument Co., Ltd
Electronic Balance, AUY220	Shimadzu Corporation (Japan)
CNC Ultrasonic Cleaner, KQ-500DB	Kunshan Ultrasonic Instruments Co., Ltd
Constant-Temperature CNC Ultrasonic Cleaner	Kunshan Ultrasonic Instruments Co., Ltd

2.2. Extraction Protocols

The experimental procedure strictly adhered to the standardized protocol regarding the determination of phthalates in electrical and electronic equipment, enacted on February 2, 2014. The laboratory employed two distinct extraction methods based on specific requirements [5]. The first method, Soxhlet Extraction, involves accurately weighing 0.5 g of the sample to the nearest 0.1 mg and placing it into the thimble of the Soxhlet extractor. A round-bottom flask containing 120 mL of ethyl acetate is prepared, and the extraction is conducted for a duration exceeding six hours, ensuring the heating rate maintains no fewer than five reflux cycles per hour. Once the solution cools to room temperature, the extract is concentrated to 5 mL using a rotary evaporator and transferred into a 25 mL volumetric flask. To ensure quantitative transfer, the round-bottom flask is rinsed with ethyl acetate in three portions, and the rinsing solution is added to the flask before making up to the mark and filtering. Alternatively, the Ultrasonic Extraction method involves accurately weighing 0.2 g of the sample into a 50 mL Erlenmeyer flask. After adding 30 mL of ethyl acetate, the sample undergoes ultrasonic extraction for 20 minutes. The extract is then transferred to a 100 mL round-bottom flask, leaving the residue behind. This process is repeated with fresh solvent two more times for a total of three cycles. The combined extracts are concentrated to approximately 4 mL using a rotary evaporator, transferred to a 10 mL volumetric flask, rinsed with 5 mL of ethyl acetate, and filled to the mark before being filtered through an organic-phase membrane.

2.3. GC-MS Analysis Conditions

Following extraction, the filtrate is subjected to Gas Chromatography-Mass Spectrometry (GC-MS) analysis under precise reference conditions to ensure reproducibility. The system utilizes a DB-5MS capillary column measuring 30 meters by 0.25 mm with a film thickness of 0.25 μm, or an equivalent column. The temperature settings are critical for accurate separation: the inlet temperature is maintained at 280°C, the interface temperature at 290°C, and the ion source temperature at 230°C. The temperature program initiates at 60°C, holding for 1 minute, before increasing at a rate of 30°C per minute until it reaches 280°C, where it is held for 10 minutes. The carrier gas employed is nitrogen with a purity of at least 99.995%, flowing at a rate of 1.2 mL/min. The injection mode uses a split-less technique with the valve opening after 1 minute. Ionization is achieved via electron ionization (EI) at an electron energy of 70 eV. For data acquisition, the measurement mode utilizes a full scan ranging from 50 amu to 500 amu for qualitative analysis, while selected ion monitoring (SIM) is employed for quantitative analysis. It is important to note that due to the presence of inseparable isomers, DINP and DIDP appear as a cluster of partially overlapping peaks rather than distinct single peaks in the chromatogram.

2.4. Calculation and Quality Control

The quantitative content of each phthalate in the sample is calculated using the external standard calibration method [6]. The formula used for this calculation is:

$$X_i = \frac{(c_i - c_0) \times V \times K}{m}$$

In this equation, X_i represents the content of phthalate esters in the sample in mg/kg, c_i is the test concentration of phthalate esters in the sample solution (mg/L), c_0 is the test concentration in the blank solution (mg/L), V is the constant volume in mL, K is the dilution factor, and m is the sample mass in grams. The calculation is performed twice, and the final result is reported as the arithmetic mean of these two values expressed to three significant figures. To ensure the reliability of these results, strict quality control measures were implemented [7]. A blank test is conducted following the standard procedure but without adding a sample. The limit of detection (LOD) is established at 50 mg/kg for DINP and DIDP, and 10 mg/kg for other phthalates. Furthermore, standard addition recovery tests were conducted for 12 phthalate esters at concentration levels of 100 mg/kg and 2,500 mg/kg, yielding recovery rates ranging from 84% to 104% for Soxhlet extraction and 86% to 109% for ultrasonic extraction. Precision is also monitored, requiring that the absolute difference between two independent test results does not exceed 10% of the arithmetic mean under repeatability conditions.

3. Results

3.1. Quantitative Analysis of Phthalate Content

The experimental phase of this research involved a rigorous comparison between two distinct types of bicycle locks manufactured by the Zhejiang ZOLi Company: the standard "ZOLi 87610 Easy Installation Bicycle Key Pink Wire Bike Cable Combination Lock" (referred to as the Ordinary Lock) and its eco-friendly counterpart (referred to as the Sustainable Lock). The GC-MS analysis was conducted strictly following the detection protocols outlined in the previous chapter, targeting specific phthalate esters known for their environmental and physiological risks [8].

The results yield a stark and scientifically significant contrast between the material compositions of the two products. The analytical data, categorized by specific phthalate types, CAS numbers, and measured concentrations, is presented in Table 3.

Table 3. Comparative Analysis of Phthalate Content in Bicycle Locks

Phthalate	CAS Number	Ordinary Lock (mg/kg)	Sustainable Lock (mg/kg)	Detection Limit (mg/kg)
DIBP-Phthalic acids, bis-iso-butyl ester	84-69-5	2,554	Not Detected	10

DBP-Dibutyl phthalate	84-74-2	132	Not Detected	10
DMEP-Bis (2-methoxyethyl) phthalate	117-82-8	Not Detected	Not Detected	10
DIPP-Diisopentylphthalate	605-50-5	Not Detected	Not Detected	10
N-pentyl-N-pentyl-isopentyl	776297-69-9	Not Detected	Not Detected	10

3.2. Analysis of Ordinary Lock Contamination

The data obtained for the Ordinary Lock reveals a high concentration of restricted plasticizers. The most alarming finding is the level of Diisobutyl phthalate (DIBP). With a measured value of 2,554 mg/kg, the concentration of DIBP in the ordinary lock components is excessively high. To put this figure into perspective, the detection limit for the experiment was set at 10 mg/kg. The amount of DIBP found is more than 255 times the lowest detectable quantity, indicating that this chemical is not merely a trace contaminant but a fundamental constituent of the plasticizers used in the lock's manufacturing.

In addition to DIBP, the analysis detected Dibutyl phthalate (DBP) at a concentration of 132 mg/kg [9]. While significantly lower than the DIBP content, this level still represents a definitive presence of toxic substances well above the detection threshold. The presence of these chemicals confirms that the traditional manufacturing processes for the ZOLi 87610 model rely heavily on phthalate-based compounds to achieve flexibility and durability in the polymer components, such as the cable coating and casing.

3.3. Performance of the Sustainable Lock

In sharp contrast, the Sustainable Lock demonstrated a pristine chemical profile. Across all tested categories, including DIBP, DBP, DMEP, DIPP, and N-pentyl, the results were consistently "Not Detected." This indicates that the concentration of these phthalates in the sustainable lock's recycled materials is effectively zero, or at least falls below the rigorous detection limit of 10 mg/kg established by the GB/T 29786 standard.

This result validates the efficacy of the sustainable manufacturing process. It proves that the recycled materials and organic dyes used in the production of the eco-friendly version do not harbor the toxic residues typically associated with virgin plastic manufacturing in the lock industry. The absence of phthalates suggests that the sustainable lock is not only environmentally viable in terms of waste reduction but is also chemically inert regarding these specific toxins.

3.4. Health Impact Assessment

The chemical composition of bicycle locks has significant implications for human health. The experiment's focus on frequently touched and contacted components during daily life is essential [10]. Bicycle locks are handled repeatedly, with users manipulating the dial, holding the cable, and securing the mechanism, often with bare hands.

Chronic exposure to phthalates and their compounds is recognized as a serious public health concern. The high levels of diisobutyl phthalate (DIBP) and dibutyl phthalate (DBP) found in ordinary locks pose potential risks, as these chemicals can migrate from the plastic product. Phthalates are known to negatively affect the endocrine system, disrupting hormonal balance and impacting multiple organs.

The long-term impact is particularly concerning for vulnerable populations. Prolonged contact with high-phthalate materials can negatively affect pregnancy success rates, child growth and development, and the reproductive systems of both younger children and adolescents [11]. Ordinary locks contain 2,554 mg/kg of DIBP, making them a source of chemical exposure that sustainable locks effectively eliminate. Therefore, sustainable locks are considered significantly healthier for human interaction, eliminating the risk of absorbing these endocrine disruptors through dermal contact.

3.5. Visual Data Interpretation

To further illustrate the magnitude of the difference between the two products, the data was visualized in Figure 1. Figure 1 plots the concentration of the detected materials against the detection limit, providing a clear comparative analysis.

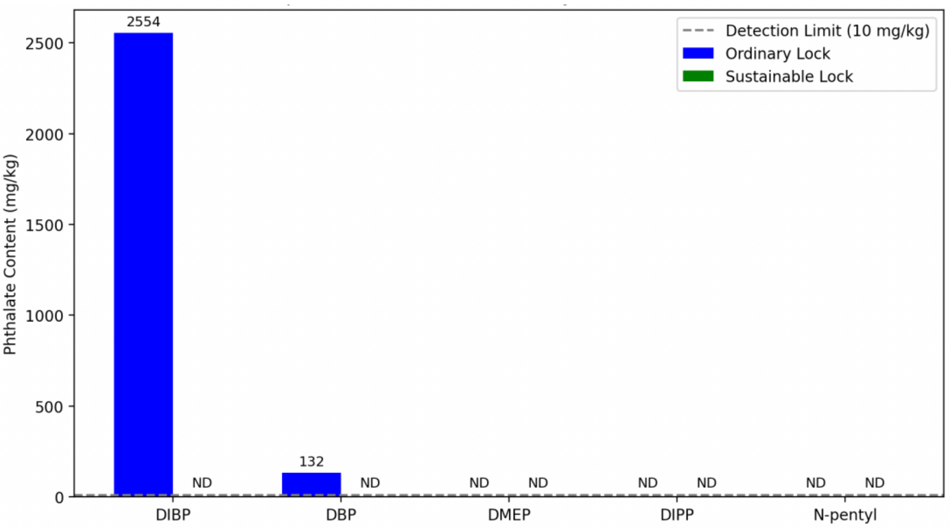

Figure 1. Comparison of Materials in Ordinary Vs. Sustainable Locks

As described in the analysis, the graph features a dotted line indicating the detection limit of 10 mg/kg. The Blue Bar, representing the ordinary lock, reaches an unusually high level for DIBP, visually dominating the chart and emphasizing the severity of the contamination. The DBP level also exceeds the threshold. Conversely, the Green Bar, representing the sustainable lock, remains at the baseline (0), visually reinforcing the "Not Detected" status.

3.6. Regulatory and Environmental Implications

The results also highlight regulatory compliance concerns. The ordinary lock contains phthalate amounts that significantly exceed permissible limits established by regulations in various importing countries. This underscores the industry's shift, as strict laws in North America and Europe have influenced China's export lock industry. The ordinary lock's high phthalate content makes it potentially non-compliant for certain international markets that prioritize consumer safety.

In contrast, the sustainable lock not only adheres to these safety standards by containing no phthalates but also aligns with environmental sustainability objectives [12]. The absence of these toxic chemicals ensures that, at the end of its lifecycle, the product can be recycled or decomposed without releasing harmful synthetic hormones into the ecosystem. This demonstrates that the sustainable lock is a superior alternative, providing the same functional utility without the associated chemical toxicity or environmental impact.

4. Discussion

4.1. Economic and Environmental Implications

Focusing on the bicycle lock industry, the advancement of recycled material application technology signifies a profound dual impact: economic and environmental. From an economic perspective, achieving a mature application of recycled materials translates directly to decreased production costs. The traditional manufacturing process for plastic bicycle lock components is expensive due to the multiple complex procedures required for polymer construction and reforming. These processes incur significant expenses in terms of energy consumption, raw material procurement, and machine maintenance. Therefore, shifting to recycled materials bypasses many of these energy-intensive steps, offering a more cost-effective production model.

Simultaneously, from an environmental standpoint, the adoption of recycled locks is crucial in addressing the challenges posed by polymers that damage and pollute the natural environment [13]. By reducing the reliance on virgin plastics, the industry can contribute to improving human living conditions and protecting environmental health from the long-term degradation caused by traditional plastic waste.

4.2. Expansion of Industry Applications

The potential of this technology extends beyond locks. As the process for producing recycled plastics advances, it can be effectively applied to other plastic-related merchandise within the bicycle industry, such as bicycle pedals and splash guards. These components require a combination of lightweight properties and high endurance for daily use. Utilizing recycled plastics or polymers in these parts could significantly transform the industry, enhancing economic efficiency in material production while maintaining performance standards.

4.3. Historical Context and Technological Evolution

The integration of plastic into bicycle production has historical precedent, though not without failure. The Itera plastic bicycle, introduced by Volvo in December 1977, serves as a critical case study. It failed because it offered no weight advantage over traditional bicycles and lacked significant innovation in structural design. At the time, consumers preferred metals for their proven resilience and endurance. However, the failure of the Itera concept was due to the technological limitations of that era. With advancements in sustainable and recycled plastics, it is now possible to explore methods to significantly enhance the strength and durability of plastic structures.

4.4. Future Outlook

The future lies in developing a bicycle lock that combines the structural endurance of conventional metals with the advantages of modern sustainability. Such a product would generate significantly less environmental pollution and decompose much faster than traditional locks [1]. This innovation holds particular importance for shared bike services globally. A bicycle fleet equipped with sustainable, biodegradable, yet durable locks could serve as a compelling advertising point for both manufacturers and sharing companies, demonstrating that durability and environmental responsibility can coexist.

5. Conclusion

In conclusion, the comparative analysis confirms that sustainable bicycle locks demonstrate significantly better performance in terms of environmental impact and biodegradability compared to ordinary bicycle locks. The comprehensive experiment presented in this study serves as definitive evidence of this advantage, highlighting a critical disparity in chemical safety between the two manufacturing approaches.

The core evidence supporting this superiority is the exceptionally low amount of phthalates found in the sustainable bicycle lock. The experimental results revealed that the presence of toxic plasticizers in the sustainable model is nearly negligible. This contrasts starkly with the chemical profile of the ordinary bicycle lock, which was found to contain 2,554 mg/kg of DIBP. This data not only validates the safety of the recycled materials but also underscores the significant chemical burden imposed by traditional manufacturing methods.

The importance of establishing a mature process for producing sustainable plastics and manufacturing components is profound, offering dual benefits from both economic and environmental perspectives. Economically, the impact of a fully developed sustainable plastic workflow is substantial. It reduces costs associated with commissioning finishers for recycled plastics, streamlining the production process. Additionally, relying on recycled sources mitigates the extra expenses incurred when raw materials are monopolized, thereby stabilizing costs. This shift can promote economic growth for manufacturers in this sector and potentially benefit other industries adopting similar sustainable workflows.

From an environmental perspective, the impact of a sustainable lock is both clear and transformative. By utilizing recycled content, the manufacturing process actively contributes to reducing plastic waste, preventing its accumulation in landfills. Furthermore, these locks exhibit strong biodegradability performance. Unlike traditional plastics that persist indefinitely, products made from these sustainable plastics can decompose naturally. This ensures that the end-of-life phase of the product leads to a cleaner environment rather than contributing to long-term pollution. Ultimately, the adoption of sustainable locks represents a necessary evolution in the industry, balancing economic efficiency with the urgent need for environmental preservation.

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