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Optimization Strategies for Waste Management in Wildlife Tourism Areas: A Systematic Literature Review

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ABSTRACT: Waste management in ecologically sensitive tourism areas has faced considerable challenges in balancing operational efficiency with environmental conservation. This study aimed to identify Solid Waste Management (SWM) optimization techniques that had been applied in tourism and conservation areas, evaluate their performance in supporting environmental sustainability, and analyze their respective strengths and limitations. The study employed a Systematic Literature Review (SLR) following the PRISMA guidelines. A total of 22 articles published between 2020 and 2026 were analyzed based on publication characteristics, study locations, optimization techniques, and their contributions to operational efficiency and habitat conservation. The review revealed that SWM optimization techniques had evolved from conventional mathematical approaches toward more integrated models through the adoption of artificial intelligence (AI), the Internet of Things (IoT), waste-to-energy technologies, and circular economy frameworks. Exact optimization models proved effective for cost minimization and transportation optimization, whereas AI and IoT supported real-time monitoring and decision-making. Waste-to-energy and circular economy approaches contributed most significantly to waste reduction, renewable energy generation, and resource recovery. Overall, the review concluded that hybrid optimization models integrating digital technologies, resource recovery, and collaborative governance represented the most promising approach for supporting efficient and sustainable waste management in wildlife conservation tourism areas.

KEYWORDS: Circular economy; waste-to-energy; resource recovery; artificial intelligence and IoT; habitat conservation

1. Introduction

The growth in visitor numbers, tourism infrastructure development, and the expansion of the service economy at nature-based destinations had resulted in a significant increase in solid waste generation, posing serious threats to environmental integrity, public health, and the degradation of fragile natural resources [1]. This condition was particularly evident at priority tourism destinations, where rapid tourism development had not been matched by adequate waste management systems [2]. The World Bank reported that approximately one-third of the world's 2.01 billion tonnes of annual municipal solid waste was not managed sustainably and projected that this amount would increase to 3.40 billion tonnes by 2050, a growth rate that exceeded global population growth. These findings demonstrated that waste management had become one of the major challenges to achieving sustainable development, particularly within the rapidly expanding tourism sector.

This problem was further compounded in wildlife tourism areas, which served the dual functions of recreational destinations and conservation zones. In these areas, efficient and timely waste management was particularly important because hazardous waste constituents could damage ecosystems, soil, and water resources that constituted essential wildlife habitats [3]. Food waste, for example, required specialized management practices to minimize adverse impacts on animal welfare and habitat hygiene [4]. Furthermore, SWM operations, including collection, transportation, treatment, and disposal, frequently exerted negative environmental and social impacts on communities surrounding protected areas [1].

The need for sustainable development in wildlife tourism areas had become increasingly urgent because of growing visitor pressure, inadequate waste management infrastructure in remote locations, and the escalating impacts of global climate change [5]. The waste generated in these areas was highly heterogeneous, ranging from biodegradable food residues to single-use plastics generated by tourism-related commercial activities [6]. Regardless of its origin or composition, solid waste required systematic management based on sustainable environmental management principles, as effective waste management represented a critical component of maintaining environmental quality and protecting wildlife habitats [7].

Waste management in wildlife tourism areas involved multiple interconnected stages, including waste reduction, collection, transportation, treatment, and resource recovery. The complexity of these activities increased as waste volumes grew, available land became more limited, and conservation areas became increasingly vulnerable to environmental disturbances [8]. These challenges were even more pronounced in geographically isolated areas, where waste collection and transportation required adaptive logistical planning and optimized operational strategies [9]. In addition, waste management systems in tourism destinations exhibited dynamic and non-linear characteristics because they were influenced by seasonal fluctuations in visitor numbers and the socioeconomic conditions of surrounding buffer communities [10].

To address these challenges, the implementation of SWM systems capable of operating efficiently while maintaining wildlife health and ecosystem sustainability required innovative technologies and advanced management approaches [11]. Optimization techniques had emerged as promising solutions through the application of mathematical models, simulation methods, and heuristic algorithms to improve waste management efficiency [12]. Previous studies demonstrated that optimization techniques could determine more efficient transportation routes to reduce carbon emissions [13] and identify suitable locations for waste treatment facilities that minimized disruption to wildlife migration pathways and natural behaviors [14]. Moreover, advances in AI and Machine Learning (ML) had facilitated the prediction of waste generation and the automatic optimization of waste sorting processes in tourism destinations [15].

Although numerous optimization techniques had been applied to waste management, most previous studies had focused on urban environments, residential areas, industrial sectors, and conventional municipal solid waste systems. Studies specifically investigating the application of optimization techniques in wildlife tourism areas remained limited and were scattered across multiple disciplines, including tourism, conservation, environmental engineering, and waste management. Wildlife tourism areas possessed unique characteristics that distinguished them from other sectors because they were required to balance tourism operations with biodiversity conservation, habitat protection, animal welfare, and environmental sustainability simultaneously. Consequently, the existing literature had not provided a comprehensive understanding of the development, effectiveness, and suitability of optimization techniques for waste management in wildlife tourism areas.

To date, several research gaps could be identified. First, the context gap reflected that most SWM optimization studies had focused on urban or industrial settings, whereas studies specifically examining wildlife tourism areas with their dual roles as recreational destinations and conservation sites remained scarce [16]. Second, the methodological gap indicated that no SLR had comprehensively classified and compared SWM optimization techniques across the entire waste management cycle, including waste reduction, collection, transportation, treatment, and resource recovery, within a single analytical framework. Third, the data gap arose because performance indicators varied substantially among studies and lacked standardization, making objective comparisons across different contexts difficult [5]. Fourth, the implementation gap showed that most existing studies remained limited to modeling or simulation, whereas studies documenting real-world implementation of optimization techniques in wildlife conservation areas, particularly in developing countries, were still very limited [3,9]. Finally, the conservation trade-off gap indicated that no previous study had explicitly examined the trade-offs among operational efficiency, technology investment, wildlife habitat conservation, and animal welfare within an integrated decision-making framework. Collectively, these research gaps highlighted the need for a more comprehensive and context-specific synthesis of the existing evidence.

This study aimed to provide a comprehensive review of SWM optimization techniques and their application in wildlife tourism areas. The novelty of this study lay in three key aspects that distinguished it from previous SWM review articles. First, it represented the first systematic review to explicitly examine the relationship between SWM optimization techniques and wildlife tourism settings, including zoos, safari parks, national parks, and conservation areas, while considering the trade-offs between operational efficiency and habitat conservation. Second, it provided a comprehensive mapping of optimization techniques, ranging from exact optimization models and AI/IoT-based approaches to waste-to-energy technologies and circular economy frameworks, according to the stages of the waste management cycle relevant to conservation areas. Third, it synthesized the available evidence to propose a Smart Circular Waste Management Framework that could serve as an operational reference for managers of wildlife tourism areas. Unlike previous SWM reviews that primarily focused on urban waste management systems [5], this study explicitly incorporated considerations of animal welfare, ecological sensitivity, and visitor behavior, thereby providing a more comprehensive framework for sustainable waste management in wildlife tourism destinations.

2. Materials and Methods

2.1. Systematic Review Protocol.

The methodology employed in this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to systematically identify, screen, evaluate, and synthesize the relevant literature [17]. This approach ensured that the review of optimization techniques in SWM was conducted in a rigorous, transparent, and reproducible manner [5]. As illustrated in Figure 1, the PRISMA 2020 framework consisted of four sequential stages: identification, screening, eligibility assessment, and data synthesis.

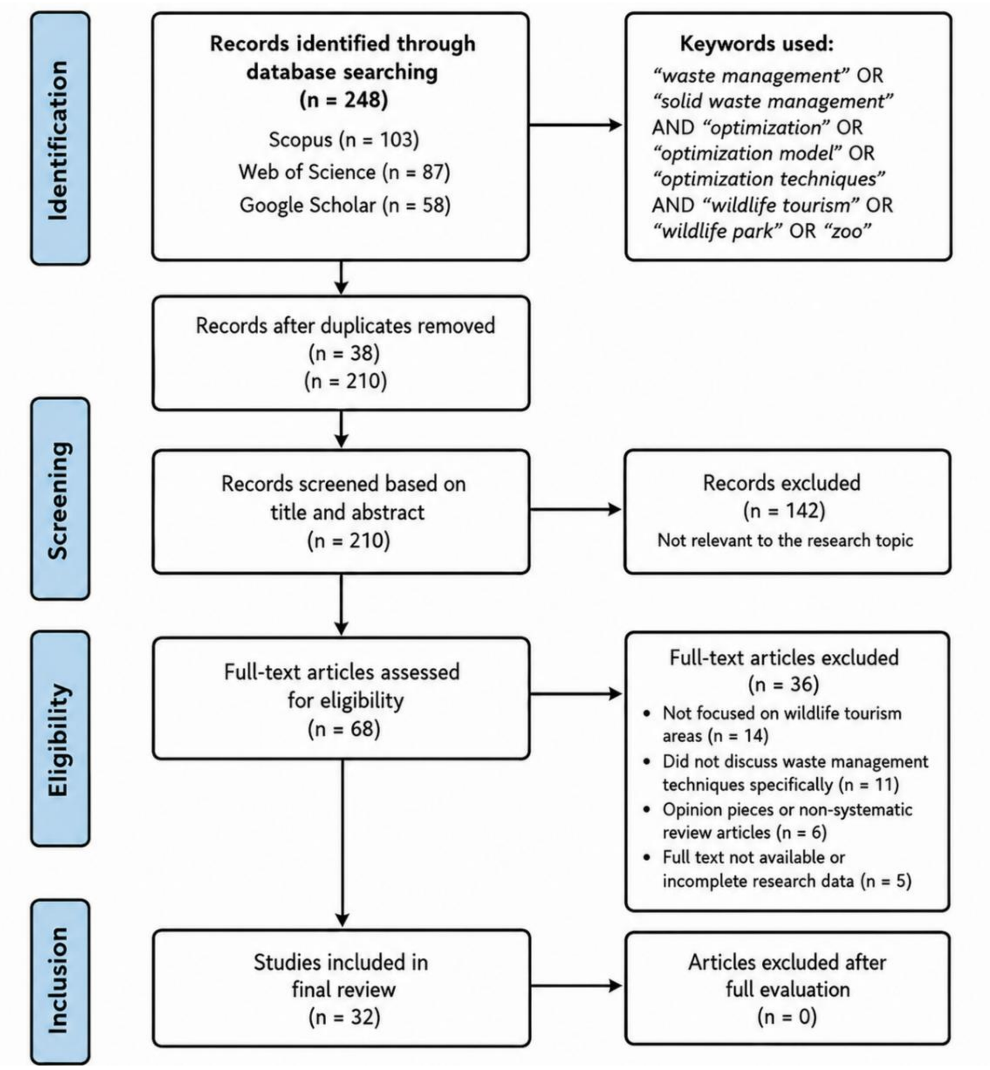

Figure 1. Systematic review methodology by PRISMA, including per-database record counts at each PRISMA stage.

The first stage involved identifying the review characteristics and defining the scope of the study. The primary objective of the SLR was to identify and evaluate published studies on the application of optimization techniques in SWM while considering the trade-offs among environmental, economic, and social dimensions [18]. To achieve this objective, the review was guided by the following research questions:

a) What studies had been conducted on SWM optimization techniques in ecologically sensitive tourism areas?

b) How did different optimization models perform in balancing operational efficiency and wildlife habitat conservation?
c) What were the strengths and limitations of applying exact, hybrid, and IoT-based optimization techniques?

As shown in Figure 1, the second stage consisted of the screening process, during which appropriate scientific databases were selected and systematic search keywords were developed to identify publications relevant to waste management optimization in wildlife tourism areas. The search strategy was designed to maximize the retrieval of relevant studies while minimizing the inclusion of unrelated publications. The third stage involved the eligibility assessment, which was conducted through abstract screening to determine whether each publication aligned with the scope of the review, namely the application of optimization techniques in waste management within wildlife tourism destinations and conservation areas. Articles that did not address waste management, optimization techniques, or the wildlife tourism context were excluded from further analysis [17]. Articles that satisfied the eligibility criteria were subsequently subjected to full-text review. This stage aimed to identify the principal findings, research contributions, optimization techniques employed, and their implications for sustainable waste management in wildlife tourism areas. Additional relevant studies were identified through snowballing (backward reference searching) by examining the reference lists of the selected publications, thereby improving the comprehensiveness of the literature review.

The fourth stage involved data synthesis and analysis. As shown in Figure 1, the selected studies were first grouped according to publication year and geographical region to identify research trends and the spatial distribution of SWM optimization studies in wildlife tourism areas [19]. The studies were then classified into four categories: Exact Models, Approximate Models, Hybrid Models, and IoT-Based Models. This classification enabled a comprehensive evaluation of the evolution of optimization techniques, the strengths and limitations of each approach, and potential research opportunities for developing more effective, efficient, and sustainable waste management systems in wildlife tourism areas [5]. The results of each PRISMA stage and the findings for the four optimization categories are presented in the following sections.

2.2. Search Strategy and Eligibility Criteria.

To address the research questions and examine the development of studies on waste management optimization in wildlife tourism areas, a systematic literature search was conducted using three international scientific databases: Scopus, Web of Science, and Google Scholar. The search strategy employed combinations of keywords related to waste management, SWM, wildlife tourism, zoo, safari park, optimization, optimization models, AI, and the IoT within the title, abstract, and keyword fields of the publications.

The initial search identified 248 potentially relevant articles. Following duplicate removal, 38 duplicate records were excluded, leaving 210 articles for title and abstract screening. The publications were subsequently evaluated according to topical relevance, document type, publication language, and the predefined publication period. During this stage, 142 articles were excluded because they did not satisfy the inclusion criteria. The remaining 68 articles underwent full-text assessment to further evaluate their relevance and methodological quality. After the eligibility assessment, 46 articles were excluded because they failed to meet the predefined selection criteria. Ultimately, 22 articles were included in the qualitative synthesis and final analysis. The complete article selection process is illustrated in Figure 1.

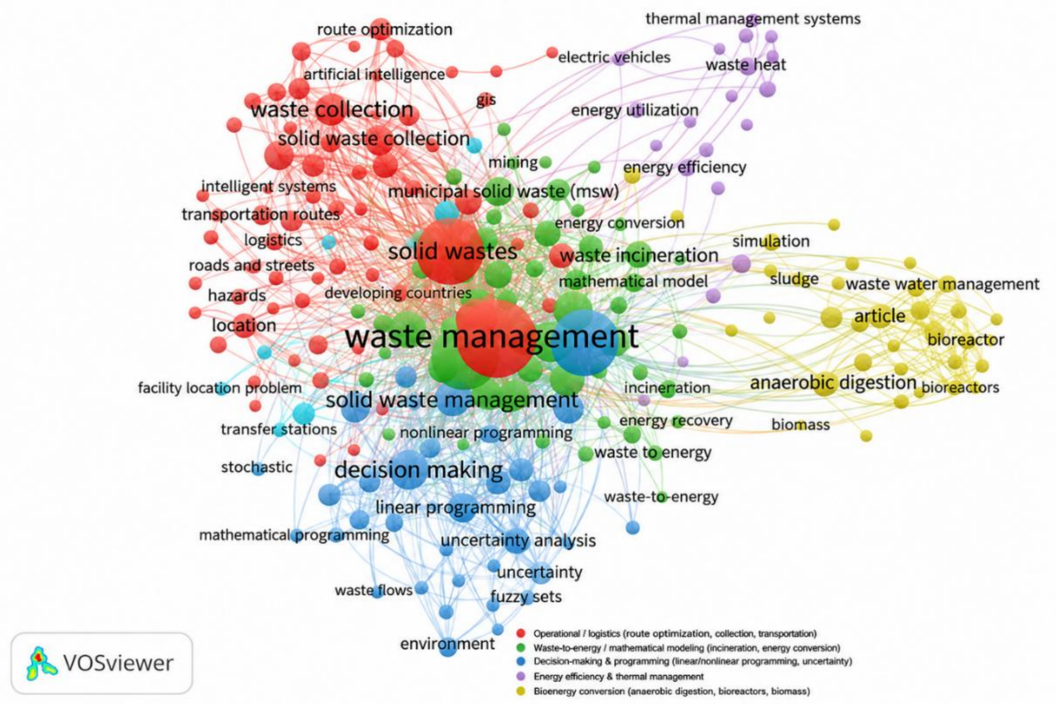

Figure 2. The keyword co-occurrence network.

In addition to the systematic literature review, a bibliometric analysis was conducted using VOSviewer version 1.6.20 to map the knowledge structure and keyword co-occurrence patterns within the selected literature. The co-occurrence analysis was performed by applying a minimum keyword occurrence threshold, resulting in several thematic clusters representing the dominant research areas. These clusters included waste management and tourism sustainability, waste management system optimization, AI and smart technologies, circular economy and resource recovery, environmental impacts, and governance and stakeholder participation. The bibliometric mapping provided a comprehensive overview of research trends, relationships among research topics, and the evolution of waste management optimization studies in wildlife tourism areas.

As shown in Figure 2, the keyword co-occurrence network revealed five dominant thematic clusters. The red cluster, comprising route optimization, waste collection, transportation, and logistics, represented studies focusing on operational efficiency. The green cluster, which included solid waste, waste incineration, mathematical models, and energy conversion, reflected research on exact optimization methods and waste-to-energy technologies. The blue cluster, containing decision-making, linear and nonlinear programming, and uncertainty analysis, represented mathematical optimization approaches. The purple cluster, consisting of energy efficiency, thermal management, and waste heat recovery, emphasized energy recovery applications, whereas the yellow cluster, including anaerobic digestion, bioreactors, and biomass, focused on bioenergy conversion technologies.

Notably, none of these five dominant clusters included wildlife tourism, zoos, safari parks, or conservation areas as central, high-frequency keywords. Instead, terms related to wildlife tourism appeared only at the periphery of the network with relatively low co-occurrence frequencies. This finding provided bibliometric evidence supporting the context gap identified in Section 1, indicating that the majority of studies on SWM optimization had concentrated on urban and industrial waste management systems, whereas wildlife tourism had remained a relatively underexplored research area. Consequently, this observation further justified the need for the present systematic review.

The relatively limited number of studies identified in this review highlighted a substantial knowledge gap regarding SWM optimization in wildlife tourism areas. Although conservation-based tourism destinations, including zoos, safari parks, and protected areas, had continued to expand alongside increasing public interest in nature-based tourism, research on effective and sustainable waste management systems within these settings had remained scarce. This research gap was particularly important because waste management practices were directly associated with habitat conservation, biodiversity protection, environmental quality, and visitor experience. Therefore, more integrated and context-specific research on SWM optimization was needed to support environmental sustainability and enhance the long-term resilience and competitiveness of wildlife tourism destinations.

2.3 Systematic Search Protocol

To ensure the reproducibility and transparency of this SLR, the search strategy was developed in accordance with the principles of systematic, transparent, and replicable evidence synthesis recommended for SLR studies [17]. The literature search was conducted using three international scientific databases—Scopus, Web of Science, and Google Scholar—by applying Boolean operators (AND, OR) and combinations of keywords covering the topical, contextual, and methodological dimensions of the research. As summarized in Table 1, the search protocol included the search strings, search dates, database-specific filters, and the number of records retrieved and retained at each stage of the screening process. Scopus and Web of Science were selected because they provide extensive coverage of high-quality, peer-reviewed journals in environmental science, engineering, tourism, and conservation research. Google Scholar was additionally included to capture regionally relevant publications, Indonesian-language studies, conference papers, and practitioner-oriented grey literature that may not have been indexed in the commercial databases. The inclusion of multiple databases improved the comprehensiveness of the literature search and helped reduce publication and language bias, which is particularly important for an emerging interdisciplinary research area such as waste management optimization in wildlife tourism [29]. The initial search retrieved 248 publications, comprising 103 records from Scopus, 87 from Web of Science, and 58 from Google Scholar. After duplicate removal, 210 unique publications remained for the screening process. Following title and abstract screening, full-text eligibility assessment, and the application of predefined inclusion and exclusion criteria, 22 studies were ultimately selected for qualitative synthesis. The distribution of records across the three databases demonstrated that Scopus contributed the largest proportion of eligible studies (10 articles), followed by Web of Science (8 articles) and Google Scholar (4 articles), indicating that high-quality research on waste management optimization in wildlife tourism has primarily been published in internationally indexed journals while still benefiting from supplementary regional and grey literature sources.

Table 1. Systematic Search Protocol (Search Protocol).

Database	Search String (Boolean)	Search Date	Additional Filters	Initial Results	After Dedup.	Final Included
Scopus	("waste management" OR "solid waste") AND ("wildlife tourism" OR "zoo" OR "safari park" OR "conservation area") AND ("optimization" OR "optimisation" OR "artificial intelligence" OR "IoT")	February 2025	2020–2026; Language: English and Indonesian; Type: Article, Review	103	94	10
Web of Science	TS=("solid waste management" OR "SWM") AND TS=("wildlife" OR "zoo" OR "ecotourism" OR "conservation tourism") AND TS=("optimization model" OR "machine learning" OR "circular economy")	February 2025	2020–2026; Language: English; Type: Article, Review, Early Access	87	76	8
Google Scholar	("pengelolaan sampah" OR "waste optimization" OR "waste management") AND ("kawasan wisata satwa" OR "kebun binatang" OR "taman safari" OR "wildlife area")	March 2025	2020–2026; Language: English and Indonesian; High relevance (top 10 pages)	58	40	4
Total (before deduplication)	—	—	—	**248**	210	22

2.4. Inclusion and Exclusion Criteria.

To ensure the validity of literature selection, inclusion and exclusion criteria were explicitly established prior to the commencement of the screening process [20]. These criteria were designed to maintain topical relevance, contextual applicability to wildlife tourism areas, and the methodological quality of the analyzed articles.

2.5. Methodological Quality Assessment (Quality Appraisal).

In addition to inclusion/exclusion screening, the methodological quality of each of the 22 included studies was assessed using an adapted MMAT/CASP checklist comprising eight criteria: (C1) clarity of the study's aim; (C2) fit between the study design and its objective; (C3) adequacy of the data or evidence sources; (C4) transparency and reproducibility of the methods; (C5) rigor of the analysis and validation; (C6) the extent to which reported results are supported by the evidence presented; (C7) whether bias and limitations were explicitly assessed; and (C8) the direct relevance of the study to the wildlife tourism/conservation context [27,28]. Each criterion was scored 0 (not met/not reported), 1 (partially met or limited), or 2 (clearly met), for a maximum total of 16 points per study. Studies were classified as High quality (13–16 points), Moderate quality (9–12 points), or Low quality (0–8 points). The specific criteria emphasized under each score were adapted to the study's design type: for systematic/narrative reviews (CASP-adapted), C3–C5 emphasized search/selection coverage and synthesis rigor; for modeling studies (MMAT-adapted), C3–C5 emphasized data/assumption adequacy and validation/sensitivity analysis; and for case studies and evaluative/mixed-methods studies (MMAT/CASP-adapted), C3–C5 emphasized sampling, data collection transparency, and triangulation.

Of the 22 included studies, 15 were rated High quality (13–16 points; e.g., Adhikari et al. [3], Alshaikh & Abdelfatah [5], Ballesteros-Álvarez et al. [14], Mukhlis et al. [10], Tin et al. [24]) and 7 were rated Moderate quality (9–12 points; e.g., Alsabt et al. [15], Aragaw [6], Bandh et al. [21], Gurung et al. [16], Kunchorn & Sharp [4], Masjhoer et al. [2], Goswami et al. [22]); no study scored in the Low-quality range. The mean total score across the 22 studies was 13.2 out of 16. Per-criterion means show that C1 (clarity of aim) and C6 (results supported by evidence) were met most consistently (mean 2.0 of 2 across all studies), whereas C5 (rigor of analysis/validation, mean 1.3) and C7 (bias/limitations, mean 1.4) were the most consistent weaknesses across the corpus—reflecting that few studies beyond the systematic reviews reported sensitivity analysis, formal validation, or explicit discussion of bias and uncertainty. No study was excluded on the basis of quality appraisal alone, consistent with common SLR practice of reporting rather than excluding lower-quality evidence in an emerging research area; the generally favorable quality distribution strengthens confidence in the synthesis presented in Sections 3 and 4, while the C5/C7 weaknesses reinforce the caution urged in Section 3.7 regarding publication bias and the indicative (rather than statistically generalizable) nature of the quantitative findings reviewed.

3. Results and Discussion

This section presents the SLR results pertaining to 22 articles that met the inclusion criteria and are relevant to the topic of SWM optimization in ecologically sensitive tourism areas. The analysis was conducted to identify research developments, publication characteristics, optimization techniques employed, the performance of optimization models in supporting operational efficiency and environmental conservation, and the strengths and limitations of each approach. The review findings were then synthesized to address the research questions concerning the types of optimization techniques that have been applied, their effectiveness in balancing efficiency and conservation, and opportunities for developing more integrated optimization models in tourism and conservation areas. The discussion is presented systematically, beginning with the characteristics of the literature, followed by the classification of optimization techniques, the evaluation of model performance, and culminating in the identification of research gaps and future development directions.

Table 2. Literature Review Matrix of SWM Optimization Research.

No.	Reference	Study Context	Optimization Approach	Main Findings	Limitation	Contribution to This Review
1	Abdallah et al. [8]	UAE	Multi-objective optimization (Fuzzy AHP)	Improved profitability (288%), reduced carbon emissions (97.6%), and generated renewable energy.	Simulation-based; requires complete datasets.	Demonstrated the effectiveness of integrated optimization for balancing economic and environmental objectives.
2	Abubakar et al. [1]	Global South	Literature review	Sustainable SWM improved environmental quality, public health, and SDGs.	Descriptive review without optimization modeling.	Established the sustainability context for SWM.
3	Adhikari et al. [3]	Nepal	Community-based management	Tourism growth increased waste generation while infrastructure remained insufficient.	Single case study.	Highlighted infrastructure and participation challenges in tourism areas.

No.	Reference	Study Context	Optimization Approach	Main Findings	Limitation	Contribution to This Review
4	Alsabt et al. [15]	Saudi Arabia	AI and Machine Learning	AI improved collection efficiency, waste sorting, and operational costs.	Model-based evaluation only.	Demonstrated the potential of AI-enabled smart waste management.
5	Alshaikh & Abdelfatah [5]	Global	Systematic review	Optimization models enhanced operational efficiency and decision-making.	Focused primarily on urban systems.	Provided the optimization framework adopted in this review.
6	Aragaw [6]	Ethiopia	Circular economy	Circular economy reduced waste and improved resource utilization.	Conceptual discussion only.	Emphasized policy and resource recovery strategies.
7	Ballesteros-Álvarez et al. [14]	Spain	Waste-to-energy (Biogas)	Zoo waste was suitable for renewable energy production.	Limited to safety assessment.	Demonstrated biogas potential from zoo waste.
8	Bandh et al. [21]	Global	Circular economy	Circular economy promoted waste reduction and resource efficiency.	No empirical validation.	Explained the theoretical foundation of circular waste management.
9	Barma et al. [12]	Nigeria	Mathematical optimization	Improved transportation efficiency and waste management performance.	Assumed static datasets.	Demonstrated exact optimization for SWM logistics.
10	Benitez-Bravo et al. [13]	Mexico	Vehicle routing optimization	Reduced transportation costs and collection time.	Urban application only.	Validated routing optimization for SWM operations.
11	Byers et al. [7]	Nepal	Integrated planning	Policy support and visitor education strengthened SWM.	Planning study only.	Proposed an integrated planning framework for protected areas.
12	Gurung et al. [16]	Global	Sustainable tourism	Tourism promoted adoption of sustainable waste management practices.	Conceptual analysis.	Linked tourism development with sustainable SWM.
13	Kunchorn & Sharp [4]	Thailand	Waste minimization	Reduced waste generation at elephant tourism sites.	Single-site evaluation.	Demonstrated practical waste minimization in wildlife tourism.
14	Lakhouit [11]	Global	AI and IoT	Smart technologies improved collection, sorting, and recycling efficiency.	Urban-focused review.	Synthesized digital technologies for SWM.
15	Masjhoer et al. [2]	Indonesia	Program evaluation	Infrastructure and stakeholder coordination remained major barriers.	Site-specific findings.	Identified governance challenges in tourism destinations.
16	Mukhlis et al. [10]	Indonesia	Stakeholder collaboration	Multi-stakeholder collaboration improved SWM performance.	Non-conservation setting.	Highlighted governance as a success factor.
17	Noviantoro et al. [9]	Indonesia	Case study	Infrastructure, tourist behavior, and management systems constrained SWM.	Context-specific.	Identified operational barriers relevant to conservation tourism.
18	Goswami et al. [22]	India	Anaerobic digestion & composting	Integrated treatment reduced waste and generated biogas.	Review-based evidence.	Demonstrated resource recovery from zoo waste.

No.	Reference	Study Context	Optimization Approach	Main Findings	Limitation	Contribution to This Review
19	Kowalski & Makara [23]	Poland	Circular economy & biogas	Closed-loop utilization improved energy efficiency.	Single facility.	Demonstrated circular resource recovery.
20	Tin et al. [24]	Global	Waste-to-energy	Zoo waste was a viable feedstock for biogas production.	Review only.	Consolidated evidence supporting zoo waste valorization.
21	Mir & Shrivastava [25]	India	Vermicomposting	Organic zoo waste was successfully converted into fertilizer.	Single zoological park.	Demonstrated low-cost resource recovery.
22	Yusrini et al. [26]	Indonesia	Circular economy	Elephant dung was converted into commercial paper products.	Single case study.	Demonstrated value-added waste utilization in conservation tourism.

3.1. Characteristics of the Analyzed Literature.

3.1.1. Distribution of Publications by Year.

A total of 22 articles meeting the inclusion criteria were published between 2020 and 2026. The analytical results reveal a trend of increasing publications on SWM optimization, particularly in the domains of tourism areas, conservation, and circular economy-based waste management. During the early period (2020–2022), research was predominantly focused on the optimization of conventional waste management systems through mathematical models, route optimization, and sustainability studies. From 2023 to 2024, research began to shift toward waste management in tourism and conservation areas, including zoos, national parks, and nature-based tourism destinations. The most significant increase occurred in 2025, with seven publications (31.8%), the majority of which addressed the integration of *waste-to-energy* technologies, circular economy, AI, and the utilization of wildlife waste as value-added resources. This trend continued into 2026 with the emergence of research specifically examining waste management in wildlife conservation areas such as zoos and safari parks. These findings indicate that the research focus of SWM has shifted from purely operational efficiency toward waste management that can support environmental conservation, emission reduction, and sustainable tourism development.

The highest number of publications was recorded in 2025 with seven articles (31.8%), followed by 2024 and 2026 with four articles each (18.2%). Conversely, the lowest number of publications was observed in 2020 with only one article (4.5%). This pattern indicates growing academic interest in SWM optimization in recent years. In addition to the increase in publication volume, a shift in research focus has also occurred. In the early period, research largely addressed the technical and operational optimization of waste management systems. However, since 2024, research has increasingly integrated aspects of conservation, circular economy, *waste-to-energy*, AI, and wildlife waste management in ecologically sensitive tourism areas. This demonstrates that SWM optimization is increasingly regarded as an important instrument for supporting environmental sustainability and habitat conservation in conservation tourism destinations.

3.1.2. Distribution of Publications by Country.

Analysis of the 22 articles reveals that research on SWM optimization in tourism and conservation areas originates from a diverse range of countries with varying environmental characteristics and waste management systems. Countries contributing the most publications are Indonesia, India, Nepal, and various global studies not focused on any single country. The dominance of developing countries indicates that waste management in tourism and conservation areas is a significant challenge, particularly in regions experiencing rapid tourism growth and high environmental pressures. Research from Indonesia and India tends to focus on wildlife waste management, zoos, and conservation tourism destinations. Research from other countries such as the UAE, Poland, Spain, and Nigeria more commonly addresses technology optimization, bioenergy, and waste management system efficiency. The geographical diversity of the research indicates that SWM optimization is a global issue requiring approaches tailored to the environmental, social, and economic conditions of each region.

Globally-oriented publications predominate with six articles (27.3%), reflecting high international interest in the development of SWM optimization models applicable across various regional contexts. Indonesia ranks second with four articles (18.2%), followed by India with three articles (13.6%) and Nepal with two articles (9.1%). The dominance of Indonesia, India, and Nepal indicates that research on waste management in tourism and conservation areas is largely developing in countries with high biodiversity, extensive nature-based tourism destinations, and complex waste management challenges. The emergence of research from Poland, Spain, and the UAE indicates that technological innovations such as bioenergy, *waste-to-energy*, and multi-objective optimization are important focal points in the development of sustainable waste management systems.

3.1.3. Distribution of Publications by Research Location.

Analysis of the 22 articles indicates that research locations are grouped into several main categories, namely tourism and conservation areas, zoos or safari parks, urban areas, rural areas, and global or conceptual studies comprising literature reviews. This distribution demonstrates that SWM optimization research has been conducted within urban waste management systems and is increasingly being applied in ecologically sensitive areas such as national parks, zoos, and conservation-based tourism destinations. Tourism and conservation areas emerge as the most dominant research locations due to their unique waste generation characteristics, which are influenced by tourist activities, wildlife conservation, and limited waste management infrastructure. Growing attention to sustainable tourism development has driven the development of various optimization models capable of balancing operational efficiency with environmental protection.

Tourism and conservation areas were the most frequently studied research locations with seven articles, followed by urban areas with six articles and zoos/safari parks with five articles. These findings indicate that research attention is beginning to shift from conventional urban waste management systems toward areas of higher ecological sensitivity. The growing number of studies in zoos, safari parks, and conservation areas reflects increasing interest in wildlife waste management, the utilization of organic waste for energy or value-added products, and the application of circular economy principles. Research in tourism areas highlights the importance of integrating waste management, environmental conservation, and sustainable visitor experience.

3.2. Study of SWM Optimization Techniques in Ecologically Sensitive Tourism Areas.

Analysis of the 22 articles indicates that SWM optimization techniques in ecologically sensitive tourism areas are evolving toward more integrated approaches. The optimization techniques identified in the literature can be grouped into five main categories: mathematical model-based optimization, AI and IoT-based optimization, waste-to-energy optimization, circular economy and resource recovery optimization, and governance and sustainable tourism optimization. Each approach has different objectives, ranging from improving operational efficiency to reducing environmental impact and conserving habitats.

3.2.1. Mathematical Model-Based Optimization.

This approach constitutes the most widely used optimization technique in the early stage of SWM research development. Mathematical models are used to determine waste allocation, the selection of treatment facilities, and the optimization of waste transportation routes, taking into account cost, carbon emissions, and operational efficiency. Research by Abdallah et al. [8] employs multi-objective optimization and Fuzzy AHP to determine the optimal waste management strategy, considering economic, energy, and environmental aspects. The findings indicate that the optimal strategy can increase profitability by 288% and reduce carbon emissions by up to 97.6%. Barma et al. [12] developed a mathematical model to improve the efficiency of urban waste management systems, while Benitez-Bravo et al. [13] applied vehicle route optimization that successfully reduced operational costs and waste collection time. In general, mathematical models are effective in generating optimal solutions based on predetermined parameters; however, they require complete data and are relatively inflexible in adapting to real-time changes in field conditions.

3.2.2. AI and IoT-Based Optimization.

The development of digital technology has given rise to AI and IoT-based optimization approaches in waste management. These technologies enable real-time monitoring of waste bin conditions, prediction of waste generation, and more adaptive decision-making. Alsabt et al. [15] demonstrate that the use of AI and *machine learning* can improve collection and sorting efficiency while simultaneously reducing operational costs. Similar findings are reported by Lakhouit [11], who highlights the role of AI and IoT in improving the effectiveness of waste collection, sorting, and recycling through *smart waste management* systems. In ecologically sensitive tourism areas, these technologies have the potential to minimize disturbance to habitats, as waste collection can be carried out in a more planned and timely manner.

3.2.3. Waste-to-Energy Optimization.

Waste-to-energy approaches have become one of the most rapidly developing optimization techniques in recent years, particularly in wildlife conservation areas and zoos that generate large quantities of organic waste. The primary focus of this approach is to convert waste into energy sources, thereby reducing waste volumes while simultaneously improving resource efficiency. Goswami et al. [22] demonstrate that the integration of anaerobic digestion and composting can reduce waste volumes by up to 80% and produce biogas. Tin et al. [24] identify the potential of zoo waste as a feedstock for biogas production for energy purposes. Kowalski and Makara [23] developed a closed-loop circular economy system that produces biogas and meat-bone meal from animal waste, while Ballesteros-Álvarez et al. [14] examined the potential for biogas production from zoo animal waste. These findings indicate that waste-to-energy approaches improve waste management efficiency and support carbon emission reduction and the achievement of zero landfill targets.

3.2.4. Resource Recovery and Circular Economy Optimization.

The circular economy approach seeks to optimize the utilization of waste into products of economic value, thereby reducing dependence on landfills. In conservation tourism areas, this approach also functions as a medium for environmental education for visitors. Mir and Shrivastava [25] utilized organic zoo waste to produce high-quality vermicompost. Yusrini et al. [26] demonstrate that elephant dung at Bogor Safari Park can be processed into poo paper that has economic and educational value. Aragaw [6] and Bandh et al. [21] emphasize the importance of circular economy principles in supporting sustainable waste management. This approach demonstrates that waste is a resource that can be reutilized to generate economic and environmental added value.

3.2.5. Governance and Sustainable Tourism Optimization.

Beyond technical approaches, several studies emphasize the importance of governance optimization in waste management in ecologically sensitive tourism areas. This approach focuses on stakeholder collaboration, tourist education, community participation, and policy strengthening. Research by Adhikari et al. [3], Byers et al. [7], Masjhoer et al. [2], Mukhlis et al. [10], and Noviantoro et al. [9] demonstrates that the success of waste management is determined not only by technology, but also by institutional capacity and the engagement of various actors. Gurung et al. [16] and Kunchorn and Sharp [4] add that good waste management practices can improve the sustainability of tourist destinations. Based on the review findings, SWM optimization techniques in ecologically sensitive tourism areas have evolved from conventional mathematical approaches toward more integrated models. Recent trends show the dominance of waste-to-energy, circular economy, and AI/IoT-based smart technology approaches that not only improve operational efficiency but also support environmental conservation, wildlife preservation, and sustainable tourism destination management. The integration of these various approaches represents the direction for future SWM optimization model development in tourism and conservation areas.

3.3. Performance of Optimization Models in Balancing Operational Efficiency and Wildlife Habitat Conservation.

3.3.1. Operational Efficiency Achieved.

One of the primary objectives of applying optimization techniques in SWM is to improve operational efficiency through cost reduction, waste volume reduction, transportation efficiency improvement, and energy utilization optimization. Based on the review findings, various optimization models demonstrate differing capabilities in achieving these objectives, depending on the approach employed. Research by Abdallah et al. [8] shows that multi-objective optimization integrating economic, energy, and environmental aspects can increase the profitability of waste management systems by 288% compared to existing practices. This model also successfully reduces dependence on landfills through the application of waste-to-energy technology, thereby significantly reducing the volume of waste disposed of.

Benitez-Bravo et al. [13] demonstrate that waste collection route optimization can improve transportation efficiency by reducing vehicle travel distance and operating time. This transportation efficiency also reduces operational costs and contributes to decreasing fuel consumption and vehicle emissions operating in sensitive areas. Kowalski and Makara [23] developed a closed-loop circular economy system that utilizes animal waste as a bioenergy source. This system can produce biogas from 160,000 tonnes of animal waste per year—sufficient to meet the energy needs of the meat and bone meal production process. These findings indicate that waste-to-energy-based optimization can improve energy efficiency while simultaneously reducing the volume of waste that must be disposed of into the environment.
Each optimization model demonstrates strengths in different aspects of operational efficiency. Abdallah et al. [8] achieve the best performance in economic and energy aspects through a multi-objective optimization approach. Benitez-Bravo et al. [13] excel in improving transportation efficiency through waste collection route optimization. Kowalski and Makara [23] demonstrate that bioenergy-based circular economy approaches can optimize waste utilization while simultaneously improving energy efficiency. These findings indicate that waste-to-energy- and circular economy-based optimization models hold the greatest potential for generating comprehensive operational benefits, as they can reduce waste while simultaneously producing value-added energy and derived products. These approaches are considered most appropriate for application in tourism and conservation areas that require a balance between operational efficiency and environmental sustainability.

3.3.2. Contribution to Habitat and Environmental Conservation.

In addition to improving operational efficiency, SWM optimization models play an important role in supporting habitat and environmental quality conservation in ecologically sensitive tourism areas. These contributions are realized through the reduction of greenhouse gas emissions, reduction of waste disposed of to landfills, resource reutilization, and reduction of contamination risks that can disturb ecosystems and wildlife habitats. Abdallah et al. [8] demonstrate that the application of multi-objective optimization can reduce the carbon footprint by up to 97.6% compared to conventional landfill systems through improved material and energy recovery. These findings indicate that optimization models not only improve system efficiency but also contribute significantly to climate change mitigation.

In the context of wildlife waste management, Goswami et al. [22] found that the integration of anaerobic digestion and composting can reduce waste volumes by up to 80% and support the concept of zero landfill. In addition to reducing environmental contamination, this system produces biogas and compost that can be reutilized as energy sources and organic fertilizers. Tin et al. [24] confirm that zoo waste holds great potential as a feedstock for biogas production. The conversion of organic waste into renewable energy can reduce greenhouse gas emissions while simultaneously improving resource use efficiency. This approach is highly relevant for wildlife conservation areas as it can reduce environmental pressures without disturbing the ecological functions of the area.

Mir and Shrivastava [25] demonstrate that vermicomposting can transform organic zoo waste into high-quality, nutrient-rich vermicompost. In addition to reducing waste volumes, this approach supports nutrient recycling and reduces the risk of soil and water contamination around wildlife habitats. Yusrini et al. [26] show that the application of Integrated Waste Management at Bogor Safari Park successfully transforms elephant dung into economically valuable poo paper. This model supports circular economy principles while simultaneously increasing environmental awareness among visitors, so that environmental conservation is achieved not only through technology but also through education and behavioral change.

The majority of optimization models make positive contributions to habitat and environmental conservation through waste reduction, resource reutilization, and carbon emission reduction. Waste-to-energy and circular economy approaches are the most dominant models, as they are capable of generating environmental benefits alongside economic benefits. Resource recovery-based models not only reduce the environmental burden but also create added value from waste previously regarded as residue. In wildlife conservation tourism areas and zoos, these approaches are critically important as they can minimize contamination risks to wildlife habitats while supporting the operational sustainability of the area.

The review findings indicate that SWM optimization models integrating waste reduction, renewable energy utilization, and circular economy principles contribute most greatly to balancing operational needs with habitat and environmental conservation efforts. These findings suggest that the success of waste management in ecologically sensitive tourism areas is determined not only by system efficiency but also by its capacity to sustainably maintain the ecological functions of the area.

3.3.3. Trade-offs Between Efficiency and Conservation.

The application of SWM optimization techniques in ecologically sensitive tourism areas does not always yield equal benefits in terms of operational efficiency and environmental conservation. In many cases, trade-offs exist between the achievement of economic efficiency and efforts toward habitat conservation and environmental sustainability. The higher the conservation targets to be achieved, the greater the investment, technology, and resources required. Abdallah et al. [8] show that the waste management strategy generating the greatest environmental benefits requires a higher initial investment compared to conventional systems. Although capable of reducing carbon emissions by up to 97.6%, the implementation of waste-to-energy facilities and material recovery entails relatively high construction and operational costs. This indicates a compromise between short-term cost efficiency and long-term environmental benefits.

In bioenergy-based approaches, Goswami et al. [22], Tin et al. [24], and Kowalski and Makara [23] demonstrate that anaerobic digestion technology and waste-to-energy systems can reduce waste volumes and generate renewable energy. However, the success of their implementation is highly dependent on the availability of infrastructure, technical capacity, and adequate investment. In other words, high conservation benefits must often be paid for with greater management complexity. Circular economy approaches such as vermicomposting [25] and the utilization of elephant dung into poo paper [26] are relatively more straightforward to implement and require lower investment costs. Their direct contribution to emission reduction and energy production is not as substantial as that of waste-to-energy models. These approaches are more oriented toward waste reduction and resource recovery than energy optimization. AI and IoT-based technologies offer high operational efficiency through real-time monitoring and decision-making. However, the implementation of these technologies requires digital infrastructure, high investment costs, and adequate human resource capacity. In conservation areas located in remote regions, limited infrastructure can become the primary barrier to technology implementation.

Overall, no single optimization model can deliver the best performance across all aspects simultaneously. Waste-to-energy and multi-objective optimization models provide the greatest benefits in terms of operational efficiency and environmental impact reduction, yet require relatively high investment. Conversely, circular economy and sustainable governance approaches are easier to implement and yield greater social benefits, but generate more limited energy benefits. These findings indicate that tourism and conservation areas require an optimization approach that considers not only economic efficiency but also environmental sustainability and available management capacity. The most appropriate model is not one that maximizes a single objective, but rather one capable of balancing operational needs, habitat conservation, and long-term sustainability. The literature indicates that hybrid approaches combining technology, resource recovery, and collaborative governance hold the greatest potential for reducing trade-offs between operational efficiency and wildlife habitat conservation in ecologically sensitive tourism areas.

3.3.4. Comparison and Prospects of Optimization Models.

Based on the literature review findings, no single optimization model is absolutely superior across all aspects of waste management. Model effectiveness depends greatly on the objectives to be achieved, the characteristics of the area, the type of waste generated, and available resources. Nevertheless, cross-model comparisons indicate that *waste-to-energy* approaches and hybrid models integrating circular economy principles tend to provide the most comprehensive benefits in balancing operational efficiency and environmental conservation. Exact models such as multi-objective optimization and vehicle route optimization have proven effective in improving cost efficiency, transportation, and resource allocation. However, these models generally focus on operational aspects and give less consideration to real-time environmental dynamics. Conversely, AI and IoT-based models offer greater adaptive capacity through real-time monitoring and decision-making, although they require relatively large technology investment.

Waste-to-energy models demonstrate the best performance in reducing waste volumes while simultaneously generating renewable energy. In addition to providing economic benefits through energy utilization, these models also contribute to reducing greenhouse gas emissions and landfill dependence. Circular economy models focus on reutilizing waste into value-added products such as compost, vermicompost, and poo paper, thereby supporting resource conservation and increasing the economic value of waste. In ecologically sensitive tourism areas, no single model is most effective for all situations; rather, integrated hybrid models combining operational optimization, smart technologies, resource recovery, and circular economy principles tend to be the most promising in specific contexts. This approach enables more adaptive, efficient, and sustainable waste management without sacrificing environmental conservation and wildlife habitat aspects.

Based on Table 3, exact models excel in operational efficiency, particularly in cost and transportation optimization. AI/IoT models demonstrate strengths in adaptive capacity and real-time field condition monitoring. Waste-to-energy models show the best performance in waste volume reduction, energy production, and carbon emission reduction. Circular economy models make the greatest contribution to resource recovery and environmental conservation through the conversion of waste into value-added products. Waste-to-energy and circular economy models are the most promising and comprehensive approaches in the context of ecologically sensitive tourism areas, although their effectiveness is highly dependent on specific area conditions. However, the literature indicates that the combination of these various approaches within an integrated model will yield more optimal performance compared to the application of any single model in isolation. Recent research trends are directed toward the development of an Integrated Smart Circular Waste Management Model, which combines mathematical optimization, AI/IoT technology, waste-to-energy, and circular economy to achieve a balance between operational efficiency and wildlife habitat conservation.

Table 3. Comparative Effectiveness of SWM Optimization Models.

Assessment Aspect	Exact Model	AI/IoT Model	Waste-to-Energy Model	Circular Economy Model
Operational cost efficiency	High	High	Moderate–High	Moderate
Transportation efficiency	Very High	High	Low	Low
Waste volume reduction	Moderate	Moderate	Very High	High
Energy utilization	Low	Low	Very High	Low
Emission reduction	Moderate	High	Very High	High
Resource recovery	Low	Moderate	High	Very High
Real-time adaptation	Low	Very High	Moderate	Low
Support for habitat conservation	Moderate	High	High	Very High
Implementation complexity	Low	High	High	Moderate
Suitability for conservation tourism areas	Moderate	High	High	Very High

3.4. Strengths and Limitations of SWM Optimization Techniques.

Based on the literature review findings, SWM optimization techniques employed in tourism and conservation areas can be grouped into three main categories: exact optimization techniques, hybrid optimization techniques, and AI/IoT-based optimization techniques. Each approach possesses different characteristics, strengths, and limitations in supporting operational efficiency and environmental conservation. The selection of optimization techniques must consider management objectives, system complexity, data availability, and the conditions of the area being managed. Table 4 indicates that exact optimization techniques demonstrate strengths in generating accurate and optimal solutions for structured problems, such as transportation route optimization and waste treatment facility allocation. However, this approach is less capable of accommodating the dynamic changes in field conditions characteristic of tourism areas experiencing visitor number and waste generation fluctuations. Hybrid optimization techniques offer improved capacity for integrating multiple management objectives, including economic efficiency, energy utilization, and environmental conservation. This approach is considered more appropriate for conservation tourism areas with complex system characteristics and the involvement of many stakeholders.

Table 4. Strengths and Limitations of SWM Optimization Techniques.

Optimization Technique	Strengths	Limitations	Literature
Exact (Exact Optimization)	Produces mathematically optimal solutions, high accuracy, effective for cost, route, and resource allocation optimization.	Requires complete data, less flexible in adapting to changes in field conditions, and difficult to apply to highly complex systems.	Abdallah et al. [8]; Barma et al. [12]; Benitez-Bravo et al. [13]
Hybrid (Hybrid Optimization)	Can accommodate multiple objectives simultaneously (economic, environmental, energy), more flexible, and appropriate for complex systems.	More complex implementation, requires greater investment, and necessitates integration of various technologies and stakeholders.	Abdallah et al. [8]; Goswami et al. [22]; Kowalski & Makara [23]
AI and IoT	*Real-time* monitoring, prediction of waste generation, adaptive decision-making, and improvement of operational efficiency.	High initial investment, requires digital infrastructure and competent human resources, and is vulnerable to technological disruption.	Alsabt et al. [15]; Lakhouit [11]

AI and IoT-based optimization techniques provide advantages in real-time adaptation and decision-making. Nevertheless, the relatively high technology and infrastructure investment requirements constitute the primary challenge in their implementation, particularly in tourism areas located in remote regions or with limited resources. No single optimization technique is superior in all aspects. However, based on the review findings, hybrid optimization techniques integrating mathematical models, AI/IoT, and circular economy and waste-to-energy principles constitute the most promising approach for application in ecologically sensitive tourism areas, as they are capable of balancing operational efficiency with habitat and environmental conservation in a more comprehensive manner.

Critically, the choice between these technique families is rarely a matter of which is "best" in the abstract, but of which trade-offs a given site can tolerate. Exact optimization models (Table 3, Table 4) deliver the highest transportation and cost efficiency only when complete, high-quality input data are available [8, 12, 13]; in most wildlife tourism areas in developing countries, where waste-generation records are incomplete or absent, this precondition is rarely met, so the theoretical superiority of exact models is unlikely to be realized in practice. AI/IoT models offer the strongest real-time adaptability, but this advantage is conditional on reliable connectivity and technical staff capacity [11, 15]; the same remoteness that makes real-time adaptation most valuable (fluctuating, hard-to-predict visitor flows) is also where digital infrastructure is least likely to be in place, which limits near-term applicability outside well-resourced sites. Waste-to-energy models achieve the largest emissions and waste-volume reductions [8, 22, 23, 24], but this performance is bought with the highest capital investment and implementation complexity, making it applicable mainly to larger zoos and safari parks with sufficient organic waste throughput to justify the investment. Circular economy approaches are the most broadly applicable at low resource levels [6, 21, 25, 26], but their environmental and energy impact per tonne of waste processed is the smallest of the four families. Read together, these findings indicate that model selection should be driven primarily by data availability, infrastructure, and financing constraints rather than by performance metrics alone, which is the logic formalized in the decision framework.

3.5. Distinctive Characteristics of the Wildlife Tourism Context: Differences from Urban Waste Management.

The majority of SWM optimization techniques identified in this review originate from urban or industrial contexts. For the findings of this review to be relevantly transferable to the wildlife tourism area context, it is necessary to explicitly clarify why the wildlife tourism context differs operationally, ecologically, and in terms of visitor behavior. At least five critical differentiating dimensions can be identified (Table 5).

Table 5. Analytical Comparison Matrix of SWM Optimization Models in Wildlife Tourism Areas.

Analysis Dimension	Exact Model (LP/MILP/VRP)	AI/IoT Model	Waste-to-Energy	Circular Economy	Governance	Integrated Hybrid
Optimization Objective	Cost, route, allocation	*Real-time* prediction, efficiency	Waste reduction, energy	*Resource recovery*, added value	Collaboration, behavior	Multi-objective
Primary Data Input	Waste volume, cost, distance	Sensor data, time-series	Organic waste composition	Waste type, product market	Stakeholders, policy	Multi-source
Primary Output	Structured optimal solution	Adaptive decisions, alerts	Biogas, electricity, compost	Vermicompost, *poo paper*, biogas	Collaborative action plan	Comprehensive KPIs
Application Scale	City, area, routes	Smart bins, large areas	Zoos, safari parks	Conservation areas	Tourist destinations	Wildlife tourism areas
Operational Cost Reduction	Very High	High	Moderate–High	Moderate	Moderate	High
Waste Volume Reduction	Moderate	Moderate	Very High (≥70%)	High	Low–Moderate	Very High
Energy Utilization	Low	Low	Very High	Low	Not Relevant	High
Resource Recovery Rate	Low	Moderate	High	Very High	Low	Very High
GHG Emission Reduction	Moderate	High	Very High (≥97%)	High	Low	Very High
Real-time Adaptability	Low	Very High	Low	Low	Moderate	High
Implementation Complexity	Moderate	High	High	Low–Moderate	Moderate	Very High
Initial Investment	Moderate	High	Very High	Low–Moderate	Low	High
Support for Habitat Conservation	Moderate	High	High	Very High	High	Very High
Most Suitable Context	Areas with complete data & adequate infrastructure	High-visitation tourist destinations	Zoos/safari parks generating large organic waste	Conservation areas with potential for derived products	Destinations with limited institutional capacity	Medium-to-large scale wildlife tourism areas

First, from an operational standpoint, wildlife tourism areas generate a highly heterogeneous waste mixture: wildlife organic waste (feces, food scraps), visitor waste (plastics, food), and veterinary-medical waste. This heterogeneity requires a more rigorous sorting system compared to urban areas where waste is relatively more homogeneous [22,25]. Second, ecologically, wildlife tourism areas are located within or adjacent to sensitive ecosystems. The siting of treatment facilities, transportation routes, and collection frequencies must take into account wildlife migration corridors, quiet zones, and breeding areas that are absent from urban SWM planning [9,14]. Third, waste generation characteristics are strongly influenced by visitor number fluctuations that are far more extreme than urban population variations. Zoos and safari parks can experience visitor number differences between ordinary days and national holidays of up to 5–10 times, such that optimization systems must be adaptive to these drastic changes [4,16]. Fourth, animal welfare factors constitute an additional variable absent from urban SWM. Vehicle noise during collection, odors from organic waste accumulation, and contamination of wildlife drinking water sources can cause behavioral stress or disease in collection animals [3,4]. Fifth, the environmental education dimension represents a unique added value of wildlife tourism areas. Waste management in these areas is not merely an operational function, but also a medium of education for millions of visitors per year. Innovations such as poo paper from elephant dung [26] or demonstrations of biogas from wildlife waste [24] can significantly increase visitor environmental awareness. These five differences provide the basis for understanding why the direct transfer of urban SWM optimization models to the wildlife tourism context requires substantial methodological and operational adaptation.

3.6. Conceptual Framework and Decision Criteria for Model Selection.

Based on the synthesis of all review findings, a Smart Circular Waste Management Framework for Wildlife Tourism Areas was developed as the primary conceptual contribution of this study. This framework maps the flow from INPUT (waste generation characteristics of wildlife tourism areas) through management PROCESSES, OPTIMIZATION based on various techniques, to the OUTPUT and CONSERVATION IMPACT generated, accompanied by a continuous monitoring feedback loop. The framework in Figure 3 demonstrates that SWM optimization in wildlife tourism areas cannot be approached in a linear manner; rather, it requires dynamic integration among five components. At the INPUT dimension, the unique characteristics of wildlife tourism areas (waste heterogeneity, visitor fluctuations, conservation regulations) determine the appropriate PROCESS choices. The OPTIMIZATION stage then selects or combines the most suitable techniques for area conditions, generating operational OUTPUT and IMPACT on environmental conservation. The feedback loop ensures the system can adapt to changing conditions on an ongoing basis. Each component of the framework is directly traceable to the review findings synthesized in Sections 3.2–3.5. The INPUT dimension (waste heterogeneity, visitor fluctuation, ecological constraints) is derived from the wildlife-tourism-specific characteristics documented in Section 3.5 [3, 4, 9, 14, 16]. The PROCESS dimension (waste reduction, collection and transportation, treatment, resource recovery, governance) follows the waste-management-cycle categorization used to organize Section 3.2. The OPTIMIZATION layer maps directly onto the five technique families reviewed in Sections 3.2.1–3.2.5: exact models [8, 12, 13], AI/IoT [11,15], waste-to-energy [14, 22, 23, 24], and circular economy [6, 21, 25, 26]. The OUTPUT and CONSERVATION IMPACT dimensions synthesize the operational-efficiency and habitat-conservation performance evidence discussed in Sections 3.3.1–3.3.2, including the cost, emission, and resource-recovery outcomes reported by Abdallah et al. [8], Goswami et al. [22], and Yusrini et al. [26]. The continuous monitoring feedback loop reflects the adaptive, real-time management capability associated with AI/IoT approaches [11, 15] and is included to address the Conservation Trade-off Gap identified in Section 1, allowing the framework to be recalibrated as visitation patterns, waste composition, or conservation priorities change over time.

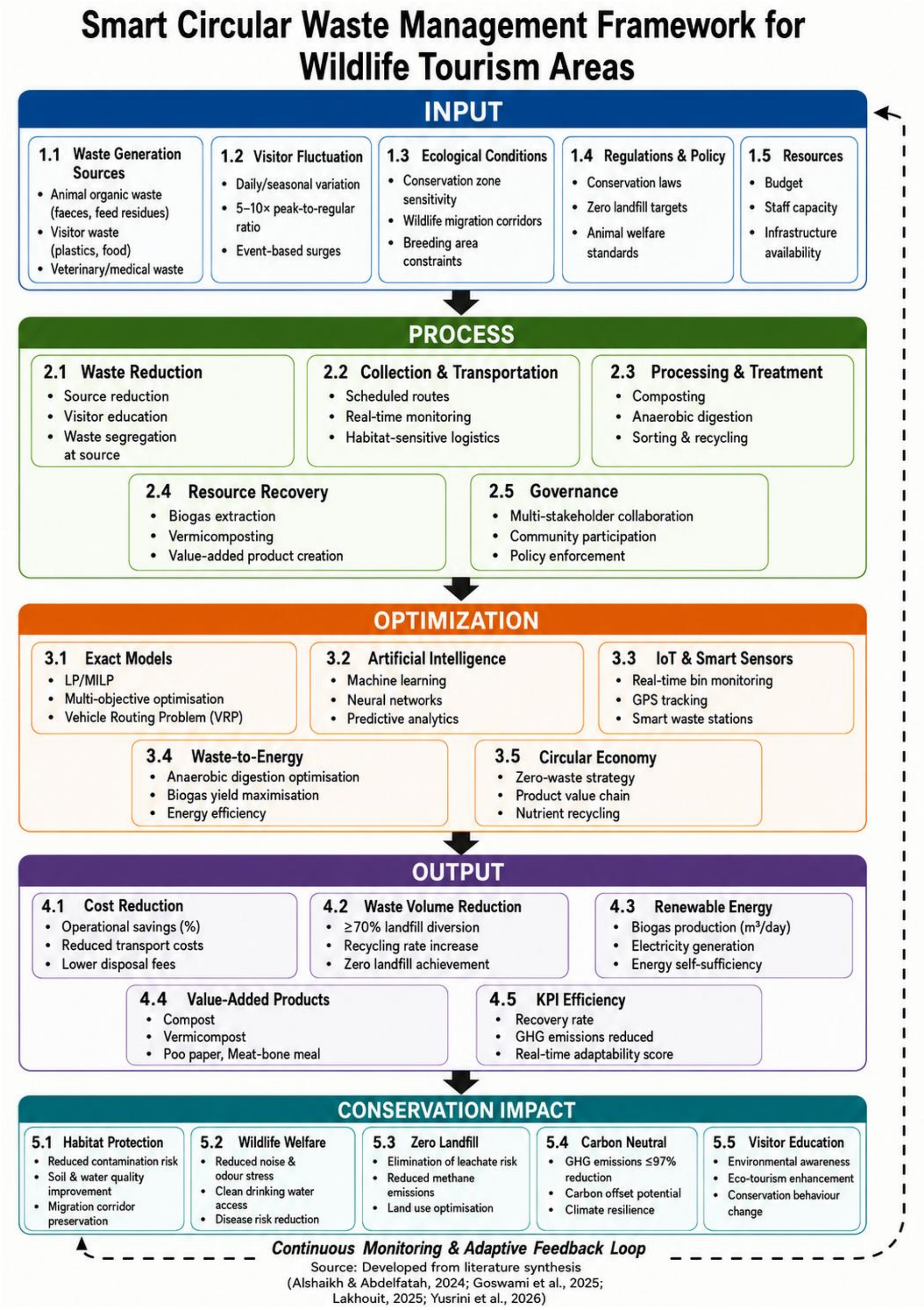

Figure 3. Smart Circular Waste Management Framework for Wildlife Tourism Areas.

The selection of an appropriate optimization model for a given wildlife tourism area is not universal but depends on the specific conditions of the area. Table 6 presents condition-based decision criteria to assist managers in selecting the most appropriate approach. Table 6 indicates that areas with limited resources should begin with low-cost circular economy approaches, while areas with high organic waste volumes (such as large zoos) can optimize waste-to-energy. High-visitation areas require AI/IoT technology for real-time adaptation. In the long term, an integrated hybrid model represents the ideal target; however, its implementation requires planned implementation stages and adequate institutional capacity.

Table 6. Decision Criteria for SWM Optimization Model Selection Based on Area Conditions.

Area Conditions	Recommended Optimization Model	Justification
Remote area, limited budget, low waste volume	Circular Economy + Collaborative Governance	Low investment; waste processed into local products (compost, vermicompost); involves local community
Zoo/safari park with large organic waste volumes	*Waste-to-Energy* (Anaerobic Digestion) + Circular Economy	High organic animal waste is suitable for biogas production; digestate residue can be used as compost
Tourist destination with high visitation and seasonal fluctuations	AI/IoT Smart Waste Management + Exact Model (VRP)	*Real-time* monitoring of bin capacity; dynamic route optimization in response to visitor fluctuations
Area with complete data and adequate technical capacity	Integrated Hybrid Model (Exact + AI/IoT + *WtE* + CE)	Maximizes multi-dimensional benefits: cost, energy, conservation, and resource recovery simultaneously
Area with high inter-stakeholder conflicts of interest	Multi-objective Optimization + Participatory Governance	Multi-objective model transparently reveals trade-offs; facilitates negotiation between efficiency and conservation

3.7. Limitations of this Review.

This review is subject to several limitations that should be considered when interpreting its findings. First, the final synthesis is based on a relatively small evidence base (n = 22). This reflects a genuine scarcity of literature at the intersection of two still-emerging research areas—SWM optimization and wildlife/conservation tourism—rather than an overly restrictive screening process: of the 68 full-text articles assessed, the majority were excluded because they addressed either optimization techniques in purely urban or industrial settings, or waste management in tourism areas without any optimization component. The small sample size limits the statistical generalizability of the quantitative performance figures reported (e.g., the 288% profitability gain and 97.6% emission reduction reported by Abdallah et al. [8]) and means the review findings should be read as an indicative synthesis of the available evidence rather than a definitive, generalizable benchmark.

Second, the search was restricted to three databases (Scopus, Web of Science, and Google Scholar) and to English- and Indonesian-language sources. Relevant studies published in other languages (e.g., Spanish, Portuguese, or Mandarin literature on zoos and safari parks in Latin America and Asia) or disseminated only as institutional or government reports may not have been captured, introducing a potential language and database-coverage bias [29]. Third, as with any literature-based synthesis, this review is susceptible to publication bias: studies reporting large, positive optimization outcomes are more likely to be published than those reporting null or negative results, which may inflate the apparent effectiveness of the techniques reviewed [29]. Fourth, most of the wildlife-tourism-specific evidence included (Table 2) originates from single-site case studies in a limited number of countries (predominantly Indonesia, India, and Nepal); findings from these contexts may not transfer directly to wildlife tourism areas in other regions with different regulatory, economic, or ecological conditions, such as the U.S. national park system [30] or Indonesian nature tourism parks outside the sites already sampled [31]. Finally, because comparable studies specifically set in wildlife tourism contexts remain scarce, several of the performance comparisons in Section 3.3 necessarily draw on evidence from general municipal or industrial SWM optimization studies [32]; these comparators strengthen the technical characterization of each optimization family but should be interpreted as indicative rather than context-validated for wildlife tourism areas specifically.

4. Conclusions

This systematic literature review of 22 studies published between 2020 and 2026 showed that research on Solid Waste Management (SWM) optimization in ecologically sensitive tourism areas has shifted from conventional operational approaches toward integrated strategies emphasizing sustainability, the circular economy, renewable energy, and environmental conservation. Exact optimization models effectively improved transportation, cost efficiency, and resource allocation, while AI and IoT enhanced real-time monitoring and decision-making. Waste-to-energy and circular economy approaches reduced waste volumes, recovered valuable resources, and generated renewable energy. Hybrid models integrating mathematical optimization, digital technologies, resource recovery, and collaborative governance emerged as the most promising solutions for balancing operational efficiency with habitat conservation. This review makes three main contributions. First, it provides the first systematic classification of SWM optimization techniques tailored to wildlife tourism areas. Second, it synthesizes evidence on the trade-offs between operational performance and environmental conservation across exact optimization, AI/IoT, waste-to-energy, and circular economy approaches. Third, it proposes a Smart Circular Waste Management Framework to support strategic decision-making rather than merely describing existing practices. From a practical perspective, waste management strategies should be selected according to site characteristics. Resource-constrained destinations should prioritize low-cost circular economy and governance measures, whereas larger zoos and safari parks with substantial organic waste streams are better suited to hybrid AI/IoT and waste-to-energy systems. Successful implementation also requires collaboration among governments, tourism managers, local communities, researchers, and the private sector, together with strengthened environmental education. Future research should develop standardized SWM performance indicators, evaluate the techno-economic feasibility of waste-to-energy systems, validate the proposed framework through field applications, and assess the impacts of SWM optimization on wildlife welfare and habitat quality.

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Author Contribution

Luqman Ash-Shiddiqie: conceptualization, methodology, formal analysis, investigation, data curation, writing – original draft, and visualization. Dwi Nowo Martono: supervision, methodology, and writing – review and editing. Sri Wahyono: supervision, validation, and writing – review and editing. All authors have read and approved the final version of the manuscript.

Competing Interest

No competing interest was reported by all authors.

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