



A circular economy model for organic waste management in a South African eco-tourism reserve

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Abstract

This dissertation presents the design, contextual adaptation, and validation of a circular food-waste valorisation model tailored for the Kalahari Reserve, an isolated eco-tourism and conservation site in the semi-arid Northern Cape region of South Africa. The research addresses a dual operational challenge prevalent in remote reserves: the substantial cost associated with importing food and the environmental challenges posed by organic waste disposal. The study employed the Design Science Research methodology, advancing through iterative phases encompassing problem identification, artefact development, contextual adaptation, and empirical validation. The artefact is composed of three interdependent subsystems: livestock feeding, bokashi fermentation, and horticultural production, that collectively form a decentralised circular supply chain, transforming organic waste into food, compost, and animal feed. Pilot studies focused on bokashi processing and livestock feeding, yielding coefficient data crucial for model calibration. Quantitative validation was performed using Statistical Process Control (SPC), regression analysis, scenario testing, Material Flow Analysis, and Circular Value Stream Mapping to evaluate process stability, yield reliability, and system synchronisation. Key performance indicators were deployed to assess circular outcomes. The model demonstrated a waste-diversion rate of 100%, a conversion rate of 100%, a resource-efficiency ratio of 0.99%, and a secondary-material substitution rate of 53%, achieving an overall System Performance Index (SPI) of 93%. The findings affirm that the artefact achieves mass-flow closure, operational stability, and high circularity under arid conditions, illustrating that decentralised circular-economy interventions are both viable and potentially transferable within similar conservation contexts. This study makes a significant contribution to the domain of Industrial Engineering by integrating Lean and Circular principles through the combined application of Material Flow Analysis (MFA), Circular Value Stream Mapping (CVSM), and Key Performance Indicator (KPI) frameworks. Additionally, it establishes a methodological framework for engineering-based circular-bioeconomy models in the Global South, thereby facilitating localised sustainability transitions in ecologically sensitive and resource-constrained settings.

Keywords: Circular economy, organic waste, protected areas, eco-tourism, circular agriculture, Material Flow Analysis, Circular Value Stream Mapping

Table Of Contents

Chapter 1	16
1 INTRODUCTION	16
1.1 Background.....	16
1.1.1 Conservation vs ecotourism: The sustainability paradox	16
1.1.2 Contextualising waste management problems.....	18
1.1.3 Industrial engineering as an integrative discipline	19
1.1.4 The concept behind the circular economy.....	20
1.1.5 Circular agriculture: From contradiction to solution	21
1.1.6 Study setting: A Kalahari Reserve.....	22
1.2 Problem statement.....	23
1.3 Research aim.....	23
1.4 Objectives	23
1.5 Field of study	24
1.6 Research scope	25
1.7 Novelty.....	26
Chapter 2	27
2 LITERATURE REVIEW.....	27
2.1 Circular economy	28
2.1.1 CE concepts and principles.....	28
2.1.2 Material flow analysis (MFA)	29
2.1.3 Value stream mapping (VSM)	30

2.1.4	Circular economy performance metrics and policy benchmarks	32
2.2	Waste management challenges in protected areas	33
2.2.1	Conventional vs. circular approaches.....	34
2.2.2	Case studies.....	34
2.3	Circular economy practices relevant to agriculture	36
2.3.1	Decentralised architectures for on-site valorisation.....	36
2.3.2	Composting	37
2.3.3	Closed-loop nutrient management	39
2.3.4	Integration of livestock (Pigs, Chickens).....	39
2.3.5	Management and safety considerations	40
2.3.6	Best practices	40
2.4	Industrial engineering attributes, enablers and barriers in circular agriculture systems	41
2.5	Arid and semi-arid classification	42
Chapter 3		43
3	RESEARCH METHODOLOGY	43
3.1	Research design: Design Science Research (DSR)	43
3.2	Phase structure and mapping to chapters	44
3.3	Methods and roles	44
3.3.1	Scoping review methodology.....	44
3.3.2	Semiotic Quality Framework (SEQUAL).....	45
3.3.3	Scenario analysis, regression validation, and statistical process control	45
3.3.4	Modelling support and performance tracking	46
3.4	Phase 1: Scoping review.....	46

3.4.1	Step 1: Define the research question	47
3.4.2	Step 2: Identify and select relevant studies	47
3.4.3	Step 3: Synthesise key findings and system requirements	47
3.4.4	Step 4: Validate findings with legislative and policy sources	47
3.5	Phase 2: Design a theoretical circular economy model.....	48
3.5.1	Step 1: Formalising system requirements from the literature	48
3.5.2	Step 2: Component identification.....	48
3.5.3	Step 3: System mapping and boundary definition	49
3.5.4	Step 4: Model visualisation.....	49
3.6	Phase 3: Verification	49
3.7	Phase 4: Validate conceptual model	50
Chapter 4		52
4.1	Chapter Orientation.....	53
4.2	Research Question	53
Chapter 5		54
5	LEGAL AND REGULATORY REQUIREMENTS	54
5.1	Introduction	54
5.2	Applicable legal instruments.....	56
5.2.1	National Environmental Management Act (107 of 1998)	57
5.2.2	National Environmental Management: Waste Act (59 of 2008).....	57
GN R.926 of 2013 - Storage of Waste.....		58
GN R.561 of 2022 - Composting of Organic Waste		58
5.2.3	National Environmental Management: Protected Areas Act (57 of 2003)	59

5.2.4	Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (36 of 1947)	59
5.2.5	National Water Act (36 of 1998)	60
5.2.6	National Waste Management Strategy (2020)	60
5.2.7	Integration of Biodiversity and Protected Area Governance	60
5.3	Chapter summary	61
Chapter 6		63
6	THEORETICAL MODEL	63
6.1	Introduction	63
6.2	Model architecture.....	63
6.3	Design rationale and requirement basis	65
6.3.1	Alignment with Design Science Research Methodology	65
6.3.2	Requirement-driven design logic.....	65
6.4	Components of the theoretical model	67
6.4.1	Waste generation nodes	67
6.4.2	Conversion and processing subsystems	67
6.4.3	Utilisation and output pathways.....	68
6.4.4	Supporting infrastructure and enablers	68
6.4.5	Summary of requirements for traceability	69
6.5	Integration and circular flows	70
6.5.1	Nutrient loop	70
6.5.2	Energy loop	71
6.5.3	Water loop	71
6.5.4	Feedback and redundancy	71

6.5.5	Governance and monitoring	71
6.6	Consolidated theoretical model artefact.....	72
6.7	Chapter summary	75
Chapter 7		77
7	CONTEXTUAL ADAPTATION AND PILOT DATA ACQUISITION AT THE KALAHARI RESERVE	77
7.1	Introduction	77
7.2	Site context and design constraints	77
7.2.1	Utilities and infrastructure	77
7.2.2	Climate and seasonality	78
7.2.3	Skills-based	78
7.2.4	Logistical isolation	78
7.2.5	Permitting and governance.....	78
7.3	Adaptation of the theoretical model to The Reserve	79
7.3.1	Pig subsystem	80
7.3.2	Chicken subsystem	81
7.3.3	Food-waste generation and source separation	82
7.3.4	Bokashi Fermentation.....	84
7.4	Data processing and derived indicators	85
7.5	Garden trial observations	88
7.6	Governance, compliance and risk controls	89
7.6.1	Legal compliance	89
7.6.2	Risk register	89
7.6.3	Governance summary	91

7.6.4	Sustainability objectives in context	92
7.6.5	Valorisation in context	92
7.7	Integration and data flow for The Reserve's pilots	93
7.8	Chapter summary	95
Chapter 8		96
8	VERIFICATION	96
8.1	Verification process	97
8.1.1	Data sources and verification evidence	98
8.2	Thematic verification	99
8.2.1	Physical and syntactic quality	101
8.2.2	Semantic quality	101
8.2.3	Pragmatic quality	102
8.2.4	Social quality	102
8.2.5	Organisational quality	103
8.3	Chapter summary	103
Chapter 9		104
9	VALIDATION OF THE CIRCULAR ECONOMY MODEL	104
9.1	Data foundation and preparation	105
9.1.1	Empirical waste-generation data	105
9.1.2	Bokashi pilot study dataset.....	108
9.2	Exploratory data behaviour and forecasting diagnostics	109
9.2.1	Validation methodology	109

9.2.2	Distributional characteristics	110
9.2.3	Input proportionality and co-variation between inflows	112
9.2.4	Temporal behaviour and forecasting potential	113
9.3	Bootstrap validation of the bokashi conversion parameters	115
9.4	Process-stability analysis	120
9.5	Implications for process capability and design capacity	124
9.5.1	Hospitality/Livestock Subsystem	124
9.5.2	Bokashi subsystem	125
9.5.3	Implications	125
9.6	Scenario analysis	125
9.6.1	Weekly steady-state behaviour	125
	Bin requirements and sensitivity	128
9.6.2	Seasonal capacity translation	129
9.6.3	Interpretation and design implications	131
9.7	Integrated model validation: Material flow analysis and circular value stream mapping	131
9.7.1	Material flow analysis	132
9.7.2	Circular value stream mapping	138
9.8	Validation through circular key performance indicators	140
9.9	6R paradigm benchmarking	141
9.10	Summary	144
	Chapter 10	145
10	CONCLUSION	145

10.1	Research overview	146
10.2	Contributions.....	147
10.2.1	Contribution to literature	147
10.2.2	Contribution to organisations.....	148
10.2.3	Contribution to individuals	148
10.3	Limitations and future research	149
10.4	Concluding remarks	150
REFERENCES		151
Appendix A.....		161

LIST OF TABLES

Table 1 Key Performance Indicators for pilot validation	33
Table 2 Comparative Analysis of Waste Management Approaches.....	34
Table 3 Anaerobic vs aerobic composting.....	37
Table 4 IE-relevant attributes, enablers, and barriers	41
Table 5 Alignment between research objectives and methodology.....	44
Table 6 Chapter 4 (Scoping Review) orientation	53
Table 7 Site context mapped against EN and CN codes	79
Table 8 Bokashi fermentation pilot: inputs and outputs (4-week cycle).....	84
Table 9 Data dictionary for the reserve's pilot studies.....	86
Table 10 Risk register	90
Table 11 SEQUAL verification summary	99
Table 12 Weekly organic-waste inflows (Hospitality and staff village).....	107
Table 13 bokashi pilot data	108
Table 14 Summary of exploratory diagnostics and methodological implications	109
Table 15 Kurtosis coefficients for weekly waste streams here	110
Table 16 Forecast model accuracy metrics (Holt vs Holt–Winters).....	113
Table 17 Bootstrap summary of bokashi conversion coefficients.....	117
Table 18 Descriptive statistics and 3σ control limits for weekly waste streams.....	121
Table 19 Hospitality-derived livestock inflows across scenario clusters	126
Table 20 Steady-state bokashi outputs, WIP accumulation, and bin requirements across scenarios.....	128
Table 21 Seasonal translation of bokashi outputs, garden-area requirements, bin utilisation and curing-capacity margins.....	130

Table 22 Material flows under Low-load steady-state conditions	133
Table 23 Material flows under Average-load steady-state conditions.....	134
Table 24 Material flows under Peak-load steady-state conditions.....	137
Table 25 Scenario results	140
Table 26 Mapping the 6R Paradigm to the CE model's features.....	143

LIST OF FIGURES

Figure 1 Conceptual flow from waste generation in conservation to enhanced conservation outcomes through IE-driven circular agriculture.....	22
Figure 2 IISE Body of Knowledge, redrawn from (IISE).....	24
Figure 3 Thematic map of CE literature.....	27
Figure 4 MFA of Circular Agricultural System (Except, 2000).....	29
Figure 5 Generic icons used in VSM by Ranganath M Singari	30
Figure 6 An example of Value stream mapping using Microsoft Visio.....	31
Figure 7 Functional block diagram of an example circular economy	64
Figure 8 Theoretical CE model	73
Figure 9 Butterfly diagram of the theoretical CE model.....	74
Figure 10 Monthly Food Waste from Hospitality operations diverted to livestock	82
Figure 11 Monthly Food Waste from village taken to landfill	83
Figure 12 MFA of The reserve's instantiation created in Rawgraphs.io.....	94
Figure 13 Normal Q-Q for Hospitality waste output	111
Figure 14 Normal QQ for staff village waste output.....	113
Figure 15 Weekly Organic-Waste Generation (Hospitality vs Staff village)	113
Figure 16 Observed vs Fitted – Hospitality waste stream	114
Figure 17 Observed vs Fitted – Staff village waste stream	115
Figure 18 Bokashi mass balance: input vs output	118
Figure 19 Distribution of bokashi conversion ratios	119
Figure 20 Boxplots of bokashi conversion ratios	120
Figure 21 Individuals-Moving-Range (I-MR) control chart for Hospitality waste stream.....	122

Figure 22 Individuals-Moving-Range (I-MR) control chart for the staff village waste stream ..	123
Figure 23 Boxplots of weekly inflows for Livestock	126
Figure 24 Boxplots of weekly inflows for Bokashi	127
Figure 25 Weekly Bokashi outputs	128
Figure 26 Seasonal cured-mass production and curing capacity under Low-, Average- and Peak-load scenarios	130
Figure 27 Material Flow Analysis diagram of the circular food-waste valorisation system	132
Figure 28 Circular Value Stream Map of The Reserve's circular economy model	139

CHAPTER 1

1 Introduction

This chapter explains the operational challenge of managing organic waste within a South African eco-tourism reserve, where conservation imperatives intersect with the resource demands of luxury hospitality. The study is situated in the field of Industrial Engineering and illustrates how analytical methodologies, specifically Material Flow Analysis and Circular Value Stream Mapping, facilitate a systems-based understanding of waste generation, nutrient flows, and process synchronisation. Furthermore, the chapter delineates the research background, problem statement, aim, objectives, and the disciplinary contribution to Industrial Engineering.

1.1 Background

The way societies manage waste directly impacts resource efficiency, environmental quality, and the effects of climate change, making it a fundamental component of broader sustainability initiatives across industries. It is widely acknowledged that transitioning from linear disposal methods to more sustainable alternatives is crucial for reducing ecological footprints, protecting natural resources, and fostering long-term socioeconomic resilience.

In South Africa, Private Protected Areas (PPAs) exemplify the intricate equilibrium between ecological management and economic viability. While they are guided by explicit sustainability objectives, such as biodiversity preservation and minimising ecological footprints, PPAs frequently face paradoxes. These contradictions are particularly evident in the domain of waste management, where the practices associated with luxury ecotourism can potentially compromise environmental goals (Roos et al., 2023).

1.1.1 Conservation vs ecotourism: The sustainability paradox

The goal of ecotourism is to strike a careful balance between protecting the environment and providing excellent visitor experiences. As stipulated in Section 17 of the National Environmental Management: Protected Areas Act (NEMPAA), areas declared as protected areas must serve one or more of the following objectives:

- To protect ecologically viable areas representative of South Africa's biological diversity and its natural landscapes and seascapes.
- To preserve the ecological integrity of those areas.
- To conserve biodiversity in those areas.

- To protect areas representative of all ecosystems, habitats and species naturally occurring in South Africa.
- To protect South Africa's threatened or rare species.
- To protect vulnerable or ecologically sensitive areas.
- To assist in ensuring the sustained supply of environmental goods and services.
- To provide for the sustainable use of natural and biological resources.
- To create or augment destinations for nature-based tourism.
- To manage the interrelationship between natural biodiversity, human settlement, and economic development.
- Generally, to contribute to human, social, cultural, spiritual and economic development.
- To rehabilitate and restore degraded ecosystems and promote the recovery of endangered and vulnerable species.

However, eco-tourism reserves naturally generate significant organic waste from hospitality services, tourist activities, and small-scale farming. Traditional linear waste disposal methods, which involve transporting waste to distant landfills, are neither environmentally nor economically sustainable (Mukwevho et al., 2024). Transporting waste to faraway landfills costs substantial money and increases greenhouse gas emissions due to long-distance logistics (Department of Environment, Forestry and Fisheries (DEFF), 2020). This makes the ecological footprint of these protected areas worse and goes against the goals of sustainability (Mukwevho et al., 2024).

The global food system throws away about 1.3 billion tonnes of food each year, which is about one-third of all food produced for human consumption (Adelodun et al., 2024; Urugo et al., 2024). In 2017, South Africa produced 19.2 million tonnes of organic waste. The National Waste Management Strategy of South Africa has set an objective to redirect 40% of waste away from landfills by the year 2025 (DEFF, 2020). Despite this, recent evaluations indicate that the nation is significantly distant from reaching this goal. Current research indicates that South Africa generates over 125 million tonnes of solid waste per annum, with the majority still disposed of in landfills (Research And Markets, 2024). Additionally, investigative reports have pointed out that comprehensive data on national waste diversion rates are lacking, suggesting that the actual levels of waste recovery are likely much lower than those reported in official statistics (Kretzmann, 2024). This ongoing discrepancy between policy aspirations and practical implementation highlights the critical need for decentralised, context-specific waste valorisation strategies, particularly in remote conservation areas, where reliance on landfills for waste disposal remains both economically burdensome and environmentally harmful.

For this reason, a sustainability paradox exists in waste management practices. This paradox arises because conservation areas are mandated to safeguard biodiversity and ecological

integrity. Nevertheless, the very activities that generate financial resources for these objectives, namely luxury ecotourism and hospitality, produce substantial volumes of organic waste. When this waste is handled using linear, landfill-dependent methods, it runs counter to conservation goals, creating a direct conflict between making money and protecting the environment.

1.1.2 Contextualising waste management problems

Protected areas, especially those situated in remote or rural parts of South Africa, face unique and acute waste management challenges. These include logistical complexity, elevated transportation costs, limited recycling infrastructure, and heightened environmental impacts. Conservation sites often rely on municipal waste systems that are themselves under strain.

A study by Mukwevho et al. (2024) looks at how Integrated Waste Management Plans (IWMPs) are being used in South African cities and towns. It finds significant problems with waste management, including insufficient infrastructure, insufficient funding, political interference, insufficient skilled workers, and weak monitoring systems. These systemic problems are even worse in remote conservation areas, where city resources are often stretched too thin.

Organic waste, predominantly food scraps, yard trimmings, and garden refuse, constitutes a significant portion of the waste stream in ecotourism and conservation contexts. According to national waste studies, the organic fraction of municipal solid waste (OFMSW) accounts for more than 40% of municipal solid waste in South Africa. This is similar to what is observed in other developing countries, where organic waste accounts for the majority of MSW (Dell'Orto and Trois, 2024).

According to the United States Environmental Protection Agency (EPA), food waste constitutes approximately 24% of municipal solid waste deposited in landfills. When considering additional contributions from yard trimmings and wood, organic materials collectively account for over 51% of landfill content (EPA, 2023). Although U.S. statistics are not directly applicable to the South African context, these figures underscore the significant global role of organic waste within the municipal solid waste (MSW) stream.

From an operational standpoint, moving organic waste long distances to remote landfill sites significantly increases logistics costs for conservation areas. When organic waste is not properly disposed of, it builds up and releases methane, a harmful greenhouse gas. It also makes soil and water more likely to become contaminated. These problems are exacerbated by the fact that institutions are often short on money, staff, and governance, making remote protected areas even less efficient.

1.1.3 Industrial engineering as an integrative discipline

Industrial Engineering (IE) offers a comprehensive, systems-based methodology for addressing sustainability challenges by integrating technical optimisation with environmental and social considerations (Parnell and Kenley). As Roopa et al. (2024) asserts, the discipline has evolved well beyond its traditional roots in manufacturing and logistics to become pivotal in sustainability-driven transformations.

According to Tsoku et al. (2024) IE is uniquely positioned to contribute to sustainability by enhancing resource efficiency, reducing environmental impacts, and improving social outcomes through integrated system design and optimisation. Tsoku et al. (2024) argue that IE's systems thinking approach, which combines people, processes, and technology, helps to reach many of the Sustainable Development Goals (SDGs), especially SDG 12 (responsible consumption and production), SDG 9 (industry, innovation, and infrastructure), and SDG 7 (affordable and clean energy). The South African context is particularly relevant, as local IE curricula are progressively aligned with these global objectives through graduate attributes mandated by the Engineering Council of South Africa (ECSA), which necessitate the incorporation of sustainability considerations in engineering problem-solving and design (Tsoku et al., 2024).

Industrial engineers utilise analytical methodologies such as Material Flow Analysis (MFA) and its circular adaptations, notably Circular Value Stream Mapping (CVSM), to measure resource flows, identify inefficiencies, and facilitate the redesign of systems aimed at reducing waste and achieving loop closure (Lombardi et al., 2021; Tsoku et al., 2024). These methodologies are especially beneficial in decentralised, resource-limited environments, where context-specific assessments of circularity are necessary to harmonise operational efficiency with environmental management.

The Lean-Green paradigm is a well-known way to connect environmental performance with operational efficiency. Carvalho et al. (2010) show that integrating Lean practices (eliminating non-value-adding activities, flow optimisation) with green practices (pollution prevention, resource efficiency) improves operational, economic, and environmental supply-chain performance when measured with a coherent set of indicators. Extending this line, Carvalho et al. (2011) argue that combining Lean and Green within broader Lean, agile, resilient, and green integration strengthens system resilience and sustainability rather than creating trade-offs, providing an anchor for using MFA and CVSM to target both process and environmental waste in PPAs.

Tsoku et al. (2024) also show that IE principles, such as systems integration, supply chain sustainability, human-centred design, and life-cycle cost analysis, are directly related to the three main pillars of sustainable engineering: environmental stewardship, economic feasibility, and

social equity. These skills make industrial engineers valuable for designing systems that can handle the unique challenges of protected areas.

1.1.4 The concept behind the circular economy

The idea of the Circular Economy (CE) emerged because the traditional "take-make-dispose" model has problems. Pearce and Turner (1989) were among the first in Western academia to formally introduce the term "circular economy." They criticised the unsustainable extraction-disposal model and proposed an economic system that accounts for environmental factors by using resources more efficiently and reducing waste.

The Ellen MacArthur Foundation (2022) built on this foundation by popularising a comprehensive CE framework based on three main ideas: eliminating waste and pollution, keeping products and materials in use, and restoring natural systems. This clarified and made these early theoretical contributions more useful in practice.

In addition to these intellectual beginnings, Europe started to make fundamental policy changes in the 1990s, especially in the UK. European waste-prevention plans and early policy discourse incorporated the "3R" principle, Reduce, Reuse, Recycle, as a stepping stone towards early circularity. UK legislation and waste-strategy initiatives in the early 1990s began reflecting systems thinking rather than purely end-of-pipe waste management, situating resource efficiency within broader economic and environmental policy frameworks (Hill, 2016). Figure 1 illustrates the fundamental distinction between linear and circular economy models. The linear model follows a one-directional flow, which typifies conventional waste management in traditional scenarios. In contrast, the circular economy model introduces feedback loops that extend resource lifecycles through reuse, recycling, and regeneration. In this system, waste is minimised by reintegrating outputs back into production or consumption cycles, thereby closing the loop and reducing reliance on virgin materials.

In industrial settings, Circular Supply Chains (CSCs) are used to put CE into action by trying to close, slow, and narrow resource flows (Geissdoerfer et al., 2018). These supply chains make products last longer, encourage reuse, and make it easier to set up take-back and recycling programs. Industrial Engineering is the design, improvement, and installation of integrated systems of people, materials, information, equipment, and energy. It draws on knowledge from many fields to maintain the flow of materials, energy, and information in industrial systems (IISE). The discipline can develop and implement closed-loop solutions that make resource flows more efficient, thereby improving sustainability performance, by leveraging its systems-thinking skills and knowledge from areas such as green supply chain management and the circular economy (Roopa et al., 2024).

This section situates CE in both academic and practical contexts by combining historical development and theoretical frameworks. It starts with Pearce and Turner's early economic critique, moves on to the 3R principle being adopted in UK and European policy in the 1990s, and ends with the Ellen MacArthur Foundation's strategic CE model.

In line with the circular economy framework, valorisation is the intentional conversion of organic waste into inputs or products of greater value (such as soil amendments through bokashi or composting, safe feed or larval biomass, and, when possible, biogas or digestate). This replaces virgin inputs, boosts ecological performance, and makes the site more resilient.

1.1.5 Circular agriculture: From contradiction to solution

Traditionally, agriculture is viewed as incompatible with conservation because it is resource-intensive and ecologically disruptive. Land clearing, water extraction, and monoculture planting are practices that can harm ecosystems and make it harder to reach biodiversity goals, which are important to conservation (Roos et al., 2023). This study challenges that dichotomy by explicitly reinterpreting agriculture through the framework of Industrial Engineering and circular-economy principles.

In this context, agriculture is regarded as a regenerative, system-optimised function: a meticulously designed intervention that enhances the value of organic waste streams generated from conservation activities. Using IE methods like MFA and CVSM, waste flows from kitchens, lodges, and small-scale processing activities can be modelled and redirected into valuable agricultural inputs, like bokashi composting or nutrient cycling systems (Department of Environment, Forestry and Fisheries (DEFF), 2020; Mukwevho et al., 2024; Merfield, 2012).

The conceptual flow of this research is illustrated in Figure 1. It reflects the integrative role of Industrial Engineering in transforming conservation waste challenges into regenerative opportunities through circular agriculture.

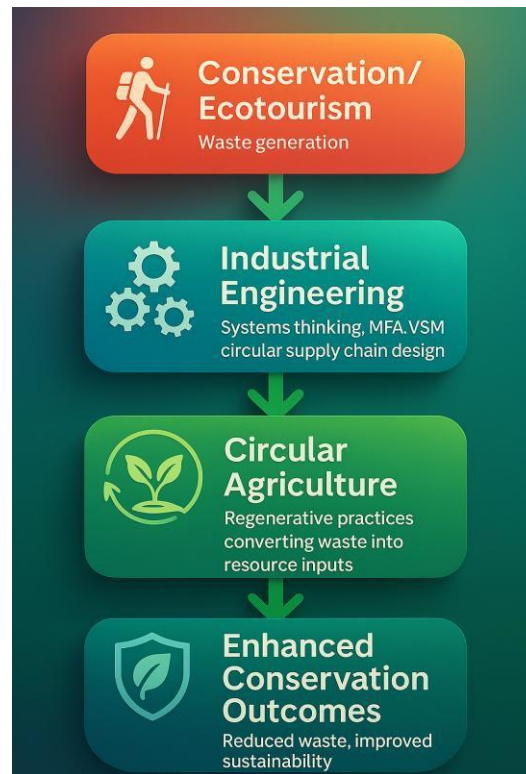


Figure 1 Conceptual flow from waste generation in conservation to enhanced conservation outcomes through IE-driven circular agriculture

1.1.6 Study setting: A Kalahari Reserve

This study was conducted in a South African protected area (PA) – “The Reserve”. The International Union for Conservation of Nature (IUCN) definition of a PA as “a clearly defined geographical space, recognised, dedicated and managed through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values” (IUCN, 2008). In this context, private protected areas (PPAs) are given special attention. The IUCN defines these areas as “under private governance that meet the IUCN PA definition,” meaning that private individuals, NGOs, corporations, or communities oversee managing them (Mitchell and J.A., 2018). South Africa has a well-established network of protected areas, including government-run national and provincial reserves, as well as a growing number of private protected areas (PPAs).

The choice of a PPA for this study is based on the unique operational problems and opportunities that these sites offer. PPAs must find a way to balance ecological sustainability with financial viability on their own, often through luxury ecotourism models. This makes them good places to investigate integrated circular-economy strategies that aim to improve sustainability, lower costs,

and support conservation goals. In this study, a remote ecotourism reserve refers to a PPA that is geographically distant from urban service hubs and municipal waste infrastructure, yet operates on-site hospitality services that generate steady organic waste streams, conditions that both intensify the costs of linear disposal and increase the potential benefits of local valorisation.

A Kalahari Reserve is the reference site for this research. Located in a semi-arid climate, a sensitive environment, and runs its hospitality businesses out of lodges. Due to these features, it is an ideal location for designing and testing on-site organic waste solutions. Despite high conservation standards and operational excellence, the reserve faces logistical and environmental challenges typical of remote regions. Sourcing fresh produce consistently is challenging, as geographic isolation requires long-distance transport from urban centres, which increases costs and carbon emissions while compromising quality due to cold-chain and scheduling constraints. Seasonal availability and variable delivery schedules further complicate menu planning for the hospitality component.

At the same time, it is always a challenge to find an effective way to deal with organic waste. Food preparation scraps, plate waste from people who eat out, and plant scraps from landscaping or on-site food production all contribute to the steady buildup of organics. In horticulture systems, waste comes from root biomass, wilted leaves, and offcuts that cannot be sold. Without decentralised processing capacity, much of this waste is sent to landfills, which runs counter to The Reserve's commitment to ecological integrity and its goal of zero waste. De Wet's (2024) earlier pilot studies have shown that it is possible to operate advanced growing systems in harsh climates.

1.2 Problem statement

The problem is that diverting the organic waste generated by ecotourism operations to landfills contradicts the organisation's sustainability objectives.

1.3 Research aim

This study aims to design a circular economy (CE) model for on-site organic waste valorisation at a remote ecotourism reserve in South Africa.

1.4 Objectives

To achieve the aim, the study will be conducted by setting the following objectives:

1. To understand general concepts such as circular economy principles, applicable Industrial Engineering methodologies, organic waste management in conservation and ecotourism settings, and circular agriculture practices through a narrative literature review.

2. To extract system requirements for a CE model using academic literature and legal documents by means of a scoping review.
3. To design a theoretical circular economy model for a remote ecotourism reserve.
4. To verify the model per literature and standards, then assess its semiotic quality using the SEQUAL framework.
5. To validate the model by applying KPI-driven scenario analysis to the parameterised Reserve's model and comparing their performance against predefined KPI thresholds.

1.5 Field of study

This study is situated within the field of Industrial Engineering (IE), specifically at the intersection of Operations Research and Analysis, Supply Chain Management, and Systems Design & Engineering, as outlined in the Industrial and Systems Engineering Body of Knowledge. Industrial Engineering is fundamentally concerned with the design, improvement, and installation of integrated systems of people, materials, information, equipment, and energy (Parnell and Kenley). The IISE Body of Knowledge identifies knowledge areas relevant to industrial engineering, as illustrated in Figure 2.



Figure 2 IISE Body of Knowledge, redrawn from (IISE)

In this research, IE methodologies, such as MFA and CVSM, rooted in Operations Engineering and Management, are applied to quantify and optimise organic waste flows in a PPA. These tools enable systematic analysis and redesign of waste management processes to make them more efficient and environmentally friendly. The study's emphasis on converting waste into productive resources via circular agriculture aligns with Supply Chain Management, particularly circular supply chains and reverse logistics, where waste is reintegrated into the system as a valuable input or returned upstream to maintain material utility. Furthermore, the comprehensive integration of subsystems, including livestock feeding, vegetable cultivation, and composting, exemplifies the implementation of Systems Design & Engineering, guaranteeing that all elements function synergistically to fulfil the sustainability goals of the PPA.

1.6 Research scope

Since the case study site is in a semi-arid area, the research was limited to literature relevant to arid and semi-arid environments. These regions are characterised by limited water availability, high evapotranspiration rates, and variable rainfall patterns, which collectively influence agricultural productivity, waste management options, and the feasibility of circular economy interventions. By prioritising studies from the Global South, particularly sub-Saharan Africa, the review ensures that the proposed model reflects environmental, socio-economic, and infrastructural conditions similar to those of the study context. This targeted focus improves the transferability of findings and guarantees that the proposed model is not only theoretically robust but also practically feasible within the climatic and socio-economic limitations of analogous regions (FAO, 2020; UNEP, 2016; Beck et al., 2018).

The Reserve constitutes the empirical foundation for model assumptions, encompassing factors such as waste management, livestock dynamics, bokashi conversion processes, climatic constraints, and logistical considerations, all of which are anchored in site-specific empirical data. This dataset establishes realistic boundaries for the system. The model's abstraction facilitates its adaptation to comparable protected areas in the Southern African region, with particular emphasis on interconnections between subsystems, the application of technology suited to arid environments, and the implementation of closed-loop systems. The model framework, calibrated using data from the Kalahari Reserve, allows replacing site-specific parameters (e.g., waste volume, livestock limits) without requiring modifications to its core structure, thereby ensuring its relevance to the Reserve and applicability to other semi-arid, off-grid conservation areas.

The scope of this study is delineated on the basis of foundational insights obtained from a preceding investigation on organic-waste valorisation conducted at the same site. The complete article, which introduced the concept of circular economies, is provided in Appendix A.

1.7 Novelty

Although Industrial Engineering has been extensively utilised in manufacturing, logistics, and healthcare systems, its methodical application to sustainability issues in remote conservation ecotourism settings, primarily through circular agricultural modelling, remains inadequately examined in the existing literature. This study makes a unique contribution by applying IE methods to a conservation-aligned field site, demonstrating how they can improve circularity, ecological performance, and operational sustainability in the management of protected areas in semi-arid Southern Africa.

CHAPTER 2

2 Literature review

This phase critically examines circular economy (CE) applications for organic waste management in conservation areas, emphasising CE principles, challenges in protected regions, and circular agricultural techniques such as bokashi composting, livestock integration, and nutrient cycling, while highlighting obstacles and deficiencies, particularly in Southern Africa. A narrative review

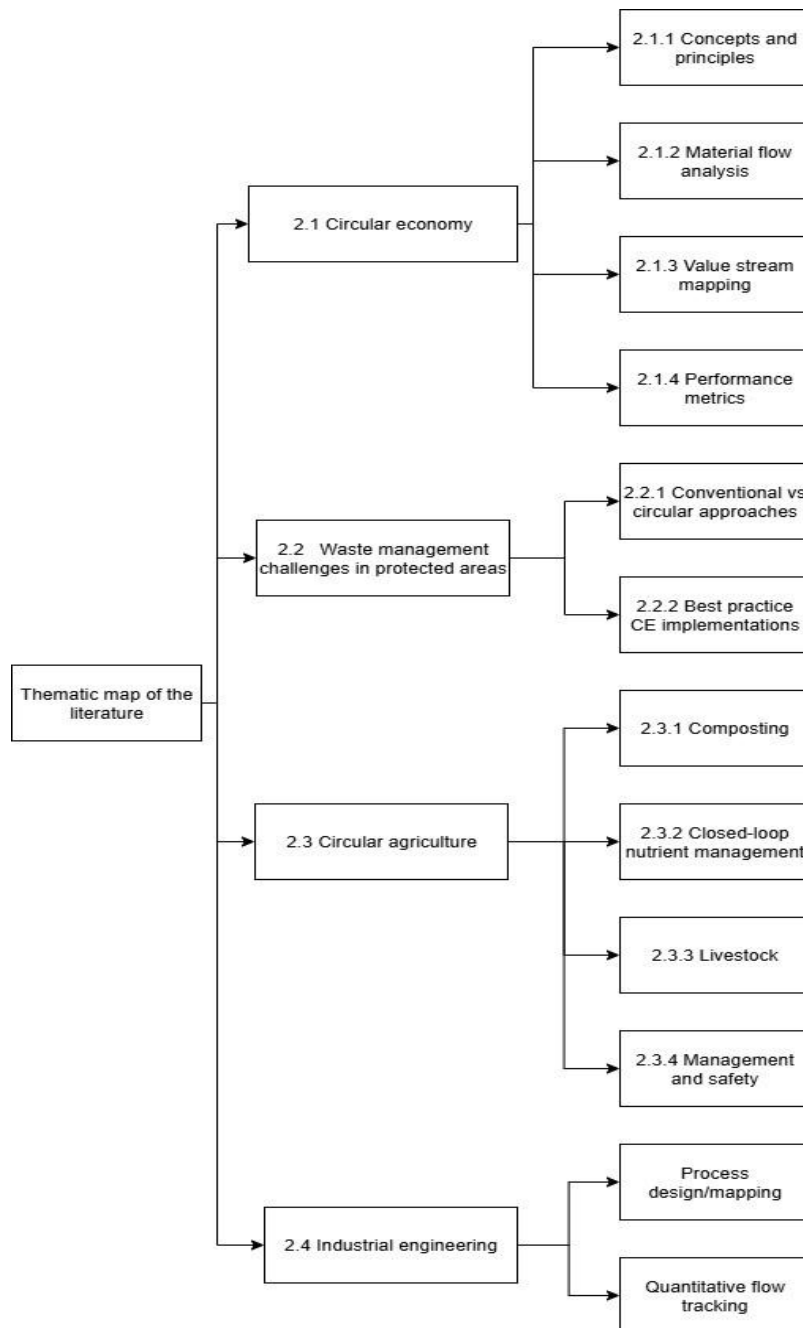


Figure 3 Thematic map of CE literature

approach was used, sourcing recent literature from Google Scholar based on thematic relevance. Figure 3 shows the breakdown of the thematic analysis.

2.1 Circular economy

The concept of a circular economy (CE) has become increasingly significant as global industries shift from traditional linear models toward sustainability-driven practices. This identifies key methodologies industrial engineers apply to advance resource optimisation and waste reduction.

2.1.1 CE concepts and principles

The circular economy (CE) differs from the current linear "take-make-dispose" economic model by separating economic growth from resource use by keeping materials and energy in closed systems. CE is, at its core, a regenerative and restorative economic model. Its goal is to keep products, parts, and materials functional and valuable for as long as possible (Hossain et al., 2024). The idea draws on a range of intellectual traditions, including cradle-to-cradle design, industrial ecology, and the performance economy. It has grown into a multi-dimensional framework that brings together environmental, economic, and social goals (De Sousa Jabbour et al., 2019).

The CE model is put into action through guiding principles that enable turning waste into resources and building strong systems. Early models focused on the 3Rs: reduce, reuse, and recycle. Since then, these ideas have evolved into more complex strategies, such as the 5Rs (refuse, reduce, reuse, repurpose, recycle), or broader R-hierarchies (Sobaih and Elnasr, 2023). In service-heavy industries like hospitality and ecotourism, these hierarchies are often used as an expanded "up to 12R" set: refuse (get rid of single-use items), rethink (product-/service-as-a-service, sharing models), reduce (resource-efficient operations and menus), reuse (durables, refill systems), repair (preventive maintenance), refurbish (furniture/equipment refresh), remanufacture (component replacement to extend life), repurpose (materials for new uses), recycle (materials recovery), recover (energy/nutrient recovery), return/reverse logistics (supplier take-back), and redistribute (surplus food donation). These strategies are supported by design principles that differentiate between biological cycles, which safely return biodegradable materials to the biosphere, and technical cycles, which recover and restore products, components, and materials for ongoing utilisation (Shwartz and Oron, 2025).

From a systems perspective, CE represents both a paradigm for conceptualising design and a methodology for reconfiguring supply chains and production systems. The efficacy of CE systems is typically quantified using metrics such as the waste diversion rate, the secondary material substitution rate, and the resource-efficiency ratio. These indicators align with the metrics

proposed in the Circularity Gap Report (2025) and have been adapted to the context of ecotourism with an emphasis on conservation.

2.1.2 Material flow analysis (MFA)

Material Flow Analysis (MFA) provides a data-driven methodology for identifying opportunities to reuse and recycle materials, as well as detecting inefficiencies within systems, as described by Brunner and Rechberger (2016). Figure 4 was extracted from Except (2000) to present a comprehensive example of the application of MFA within a circular agricultural system. This illustration delineates the movement of materials such as water, nutrients, feed, biomass, and waste across various subsystems, including hydroponics, poultry, aquaculture, mushroom production, and composting.

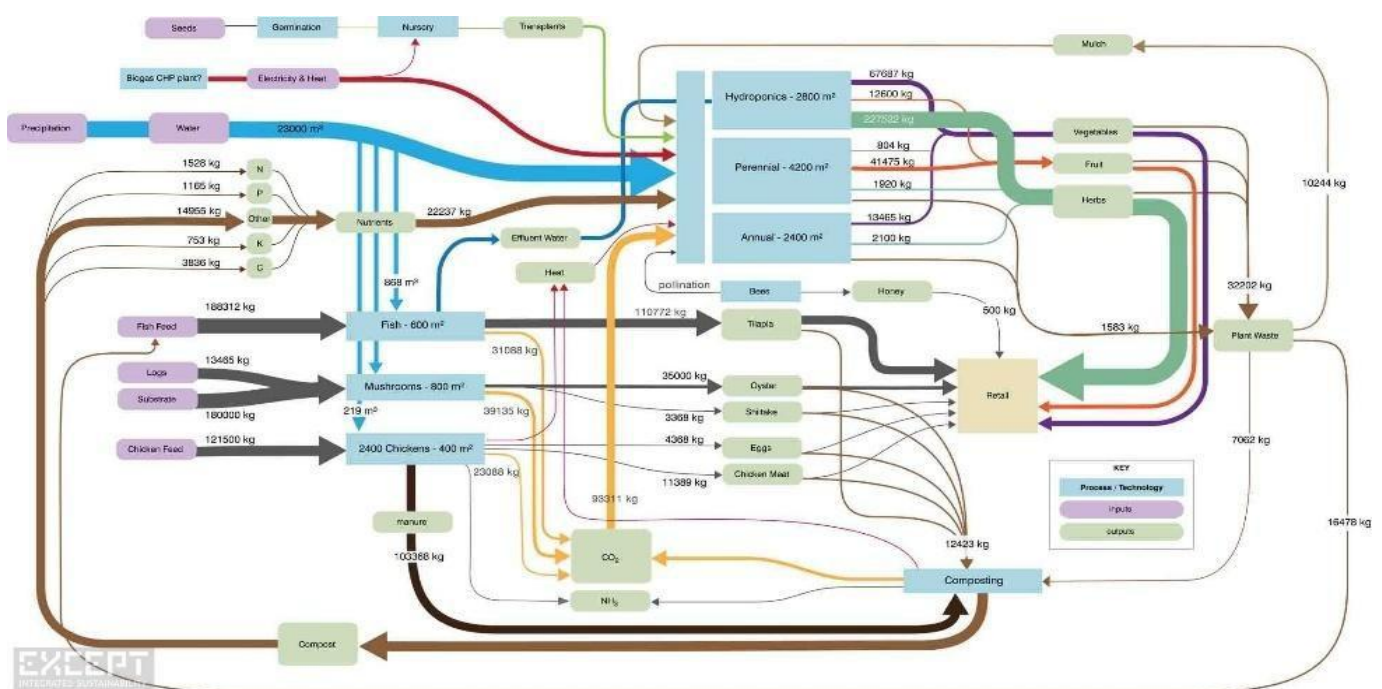


Figure 4 MFA of Circular Agricultural System (Except, 2000)

This mirrors peer-reviewed applications of MFA in circular bio-economies, for example, Dulo et al. (2022), who used MFA to measure the mass flows of over 6 Mt of biomass waste in Kenya, tracking banana, potato, and coconut residues through recovery pathways such as biogas, starch, and cellulose.

Water, primarily from precipitation, is one of the most significant inputs in the above system, with 23,000 cubic metres distributed across plant cultivation, aquaculture, and mushroom systems. Nutrients, totalling just over 22 tonnes, such as nitrogen, phosphorus, potassium, carbon, and other trace elements, are applied to crop areas. This level of nutrient quantification is consistent

with MFA approaches that close nutrient loops to maximise resource use efficiency (Dulo et al., 2022).

Other key inputs include 188 tonnes of fish feed, 121 tonnes of chicken feed, 180 tonnes of mushroom substrate, and logs used for mushroom cultivation. This is similar to what Rocchi et al. (2021) did when they adapted the Material Circularity Indicator (MCI) to biological cycles, specifically poultry. They measured inputs, outputs, and nutrient reuse in a circular production model integrated with Life Cycle Assessment.

Overall, the diagram depicts a fully integrated food production system in which biological processes support one another. Rather than treating waste as a problem, it is viewed as a resource. This makes the system strong, efficient, and aligned with the principles of a circular economy, reducing its environmental impact and increasing productivity.

2.1.3 Value stream mapping (VSM)

Value Stream Mapping (VSM) is a Lean methodology first developed for use in manufacturing settings (Jacobs et al., 2011) that systematically visualises every step, both value-adding and non-value-adding, across material and information flows. According to the U.S. EPA Lean Toolkit (US EPA, 2007), value stream mapping provides a structured way to capture and understand the sequence of activities in production or service delivery, identify non-value-adding steps (wastes), and envision a Leaner, less wasteful future state. Figure 5 shows some of the most used icons in VSM, while Figure 6 shows an example VSM.

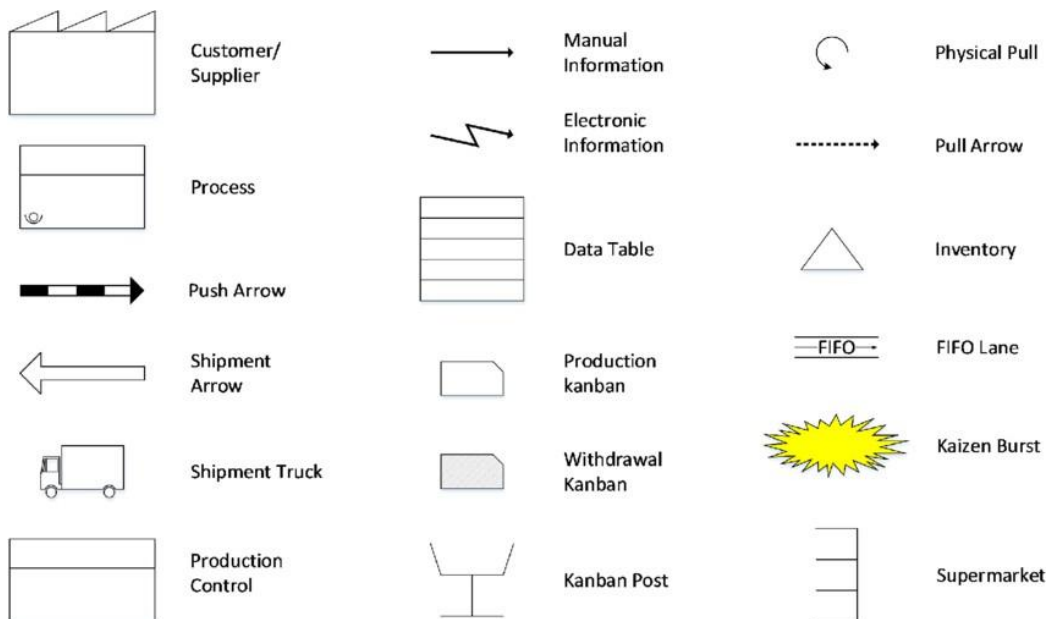


Figure 5 Generic icons used in VSM by Ranganath M Singari

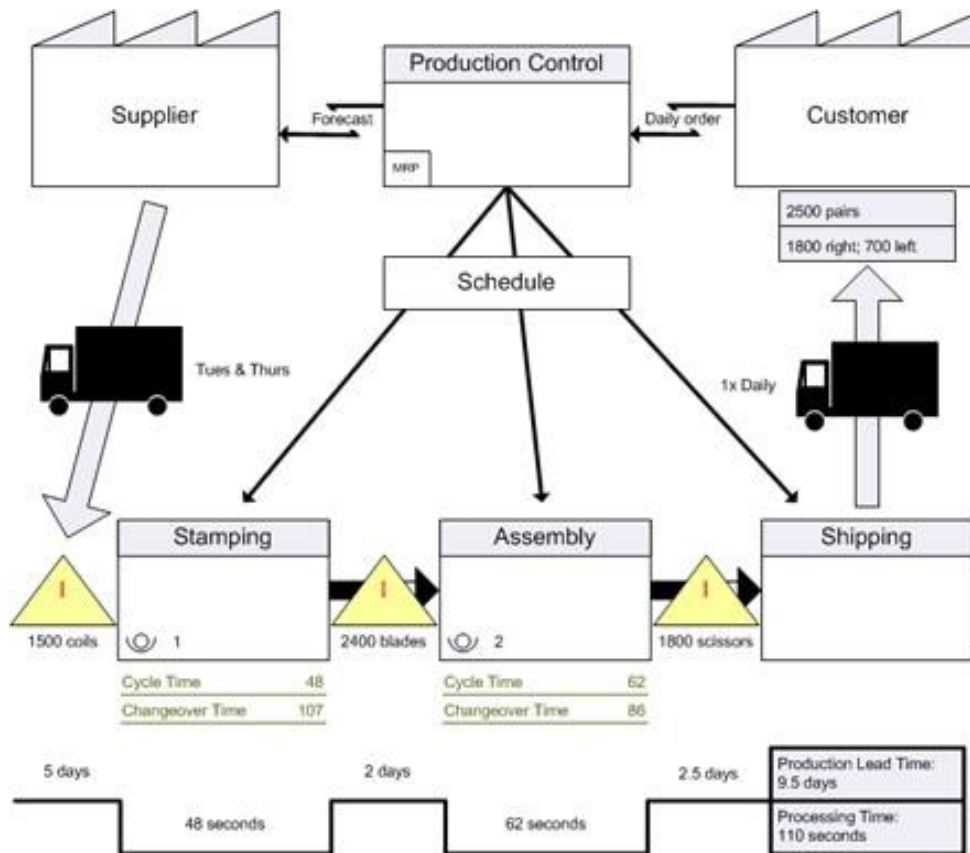


Figure 6 An example of Value stream mapping using Microsoft Visio

When repurposed for circular economy (CE) and sustainability-oriented applications, VSM becomes an even more powerful tool. Phuong and Guidat (2018) developed Sustainable Value Stream Mapping (SVSM), integrating environmental metrics, ergonomic data, and Industry 4.0 technologies (e.g., RFID, energy sensors) to map and optimise apparel-production processes, achieving significant reductions in lead time, material use, and process inefficiencies.

Applied within ecotourism operations, such as protected areas or Private Protected Areas (PPAs), VSM (and SVSM) can be adapted to map resource flows from kitchens, lodges, and agricultural units, where organic waste outputs are currently treated as liabilities. SVSM identifies inefficiencies and redesigns waste pathways into productive loops, such as on-site composting, bokashi systems, or feedstock conversion, by mapping both material flows and environmental metrics (e.g., waste volume, transport distance, and GHG emissions).

This approach aligns with CE objectives by:

- exposing bottlenecks and waste hotspots,
- enabling process redesigns that eliminate transport or disposal inefficiencies,
- supporting closed-loop systems that reintegrate outputs into production, and
- enabling Lean and green synergy through data-driven, IE-based optimisation.

Lean and Continuous Improvement methods are also essential for CE to move forward. These methods are all about systematically eliminating waste and continually improving processes. For example, VSM, when modified for CE charts and material flows, provides ways to reduce waste and close loops (Nadeem et al., 2025). In the context of CE, they support the creation of supply chains that are more flexible and robust, in which materials and products are reused, refurbished, and recycled rather than discarded (Lieder and Rashid, 2016).

Various adaptations of VSM, including Sustainable VSM, Energy/Environmental VSM, and Circular VSM, offer significant enhancements for the analysis of resource flows. Among these, Circular Value Stream Mapping (CVSM) is particularly applicable to interventions within the circular economy, specifically in ecotourism contexts, due to its explicit visualisation of loop-closure pathways, reverse flows, and reintegration points within a system (Marquina et al., 2021; de Mattos Nascimento et al., 2022). Nevertheless, CVSM remains predominantly qualitative and lacks the mass-balance precision necessary to evaluate system stability or measure circular performance metrics. In contrast, Material Flow Analysis (MFA) provides a rigorous quantitative assessment of inputs, outputs, stocks, and losses within a specified boundary, thereby facilitating the calculation of circularity indicators and performance ratios. The integration of CVSM with MFA thus delivers both structural clarity and analytical robustness: while CVSM elucidates the configuration of circular loops, MFA substantiates whether these loops achieve tangible material closure and operational feasibility. This integrated methodology is therefore better suited for modelling decentralised circular systems in remote conservation environments.

2.1.4 Circular economy performance metrics and policy benchmarks

The key performance indicator (KPI) targets for validation are based on widely accepted circular economy (CE) performance benchmarks from the literature, policy frameworks, and industry standards. The National Waste Management Strategy (NWMS) (DEFF, 2020) and the National Environmental Management: Waste Act (NEMWA, 2008) both emphasise reducing reliance on landfills and promoting sustainable waste management. Resource efficiency and conversion targets are based on current CE implementations, especially Lombardi et al. (2021). On the other hand, substitution and biomass sustainability thresholds are based on guidelines from trusted sources, such as the Circularity Gap Report 2025 (Circle Economy, 2025) and FAO (2017) best practices. The key performance indicators (KPIs) outlined in Table 1 provide a comprehensive framework for validating the conceptual model within an ecotourism reserve.

Table 1 Key Performance Indicators for pilot validation

KPI	Description	Formula	Target	Data Source
Waste-diversion rate (%)	Percentage of organic waste diverted from landfill through recycling, composting, animal feed, and reuse.	$(\text{Diverted Waste} \div \text{Total Waste Generated}) \times 100$	$\geq 80\%$	MFA
Waste-conversion rate (%)	Proportion of diverted waste converted into usable products	$(\text{Waste converted into products} \div \text{Diverted waste}) \times 100$	$\geq 60\%$	Production logs
Resource-efficiency ratio (kg/kg)	The efficiency of resource utilisation is measured as kg of usable output per kg of input.	$(\text{Mass of usable outputs} \div \text{Mass of total inputs})$	$\geq 80\%$	MFA & VSM
Secondary-material substitution rate (%)	Amount of commercial fertiliser or animal feed replaced by on-site generated products.	$(\text{Virgin material avoided} \div \text{Baseline requirement}) \times 100$	$\geq 50\%$	Procurement & production records
Overall system performance index (SPI, 0–100)	A composite index synthesising KPIs of diversion, conversion, substitution, and efficiency into a single value.	$0.25(\text{Diversion}) + 0.25(\text{Conversion}) + 0.25(\text{Substitution}) + 0.25(\text{Resource efficiency normalised})$	≥ 70	Calculated from other KPIs

The waste-diversion rate ($\geq 80\%$) and controlled-disposal rate (100%) are based on South Africa's National Waste Management Strategy (2020) and National Environmental Management: Waste Act (2008). These laws place significant emphasis on reducing landfill use and ensuring safe disposal. The waste-conversion rate ($\geq 60\%$) and resource-efficiency ratio ($\geq 80\%$) draw on best practices from Lombardi et al. (2021) and value stream mapping, ensuring efficient resource utilisation. Additionally, the secondary-material substitution rate ($\geq 50\%$) and the reserve-level circularity metric ($\geq 25\%$) align with the guidelines of the Circularity Gap Report (2025) and the FAO (2017), promoting sustainable biomass use and circularity. The overall system performance index (≥ 70) is a composite metric that combines these KPIs to give a complete picture based on data from material flow analysis, production logs, and procurement records. It is specific to the study's South African context.

2.2 Waste management challenges in protected areas

There are special challenges in waste management in conservation areas because they are remote, have fragile ecosystems, and are hard to reach. This section examines these problems

and compares traditional linear disposal methods with new circular approaches in ecotourism settings focused on conservation.

2.2.1 Conventional vs. circular approaches

Linear methods, like landfilling, are often used for traditional waste management in conservation areas. This method poses environmental risks, including the release of methane and the generation of leachate. On the other hand, circular economy (CE) strategies such as composting and anaerobic digestion convert waste into useful resources, thereby making them more sustainable (Lombardi et al., 2021).

Table 2 compares these two methods and shows that landfilling has a significant environmental impact and incurs substantial long-term costs. At the same time, on-site valorisation reduces emissions and saves money by recovering resources. However, because CE methods are not particularly complicated to set up, they must be carefully configured initially, especially in remote areas. This comparison shows how CE strategies could make things more sustainable, but they need to be adopted in a way that balances the difficulties of setting them up with their environmental benefits.

Table 2: Comparative Analysis of Waste Management Approaches

Criterion	Linear Approach (Landfilling)	Circular Approach (On-site Valorisation)
Environmental Impact	High (GHG emissions, leachate)	Low (resource recovery, reduced emissions)
Logistical Complexity	Moderate to High	Moderate (requires initial setup)
Cost-effectiveness	Short-term low, long-term high	Long-term savings through resource recovery
Sustainability Benefits	Minimal	Significant (aligns with CE principles)

2.2.2 Case studies

Ecotourism-focused reserves are implementing Circular Economy (CE) strategies to manage organic materials locally and reduce transportation distances, in alignment with protected-area directives on source separation and contextually suitable technologies (Leung et al., 2018).

Komodo National Park, Indonesia: on-site composting and a waste-bank model

Around the Komodo gateway at Labuan Bajo, a community waste-bank cooperative separates materials and supports local treatment with training and composting education (September and Firmansyah, 2017). According to the FAO, it is normal to regularly check moisture, temperature, and pH levels in small composting systems. The FAO says that the best moisture levels are around 50-60% at the start and that too much moisture should be avoided because it can cause anaerobic conditions. As compost matures, the pH should stay close to neutral. Focussing on training and simple operational routines is similar to how protected areas work, where managing behaviour and staff capacity keep on-site systems running over time (Leung et al., 2018).

Galápagos Islands, Ecuador: decentralised bio-digestion

Studies of municipal solid waste in the Galápagos identify tourism-linked pressures and the need for local treatment within a fragile ecosystem (Ragazzi et al., 2014). Programme accounts describe compact biodigesters installed near kitchens that convert source-separated food scraps into biogas for cooking and digestate for agriculture (Diez, 2024). Anaerobic digestion of food waste is effective when workers are trained, pH and temperature are maintained within mesophilic ranges, and the process is regularly monitored (Banks et al., 2018). The US EPA (2020) recommends that operators focus on feed preparation, hygiene, and regular checks to maintain high gas yields. Following protected-area rules, it is best to carefully place things away from sensitive habitats (Leung et al., 2018). Reviews of household and small-scale digesters indicate frequent early failures associated with design, construction, and operational limitations, particularly in contexts with inadequate support systems (Bond and Templeton, 2011; Shabbirahmed et al., 2024).

Implications and challenges

Both cases demonstrate that local biological valorisation is achievable when participation supports sorting and daily routines (Leung et al., 2018). Basic process monitoring helps prevent common problems that can occur during composting and anaerobic digestion, such as controlling pH and moisture levels in compost and having operators regularly check digesters (FAO; US EPA, 2020). In island and remote areas where logistics are expensive and reliability margins are low, start-up help in the form of money, training, and simple standards is often needed (UNEP, 2019). The evidence collectively suggests that localised treatment involving nutrient or energy recovery aligns with the limitations and anticipations of conservation environments (Ragazzi et al., 2014).

2.3 Circular economy practices relevant to agriculture.

Despite growing recognition of the circular economy as a systemic necessity, its current application is predominantly concentrated in a limited number of sectors, notably waste management and plastics. Consequently, numerous fields, including agriculture, food systems, and water management, remain substantially under-represented in circular economy strategies (OECD, 2021). In agriculture, circular economy (CE) strategies aim to close nutrient and resource loops, reduce waste, and make the environment more sustainable by using new ways to reuse and recycle materials. Key practices include composting methods such as bokashi, livestock integration for organic waste valorisation, and advanced nutrient recycling systems that enhance soil fertility and minimise environmental harm.

2.3.1 Decentralised architectures for on-site valorisation

Decentralised architectures collocate resource-recovery units at or near the point of waste generation, using source separation and modular treatment to convert organics and side-streams into energy, nutrients, and materials. Compared with centralised, end-of-pipe solutions, decentralisation can increase recovery yields, reduce haulage, and improve resilience, especially where transport is costly or constrained (Garrido-Baserba et al., 2024).

Liquid-stream valorisation

Urine-diverting and side-stream configurations enable compact nutrient recovery, e.g. struvite precipitation and ammonia stripping, at high efficiencies when operated near source; recent techno-economic analysis reports around 89% N and 99% P recovery under decentralised scenarios (Wu et al., 2024), consistent with earlier experimental work on struvite processes (Morales et al., 2013).

Organic-solids valorisation

Containerised black soldier fly larvae units convert segregated food waste into insect protein and frass for soil application. Evidence supports high diversion with favourable environmental profiles in many settings (Rehman et al., 2023). Nonetheless, direct measurements show GHG emissions can vary with growth dynamics and operating conditions (Boakye-Yiadom et al., 2022), while LCA under composting-oriented configurations has even reported net-negative treatment-stage emissions, underscoring the importance of configuration and boundary choice (Ramzy et al., 2025).

Small-scale anaerobic digestion (AD). Micro- and portable digesters produce biogas and digestate from kitchen scraps and manures (Issahaku et al., 2024). Modular pyrolysers stabilise

lignocellulosic residues into biochar (with co-products for heat/power), reducing wet-waste transport and enabling on-site carbon storage (Dubey et al., 2025). Emerging analyses of small, distributed units highlight niche competitiveness at modest scales (Dubey et al., 2025).

Architecture and control

Effective decentralisation uses modularity (plug-and-play), redundancy, and light telemetry (bin scales, flow meters, SPC dashboards) to maintain mass-balance closure, trigger maintenance, and orchestrate functional coupling (Reymond et al., 2020). In practice, governance and monitoring arrangements adapted from small-scale sanitation are essential to ensure product safety and compliance (Ventura et al., 2024).

For isolated reserves, a hub-and-spoke array of these modules can cut landfill dependency, reduce freight-related scope-3 emissions, and produce local energy and fertilisers, provided source separation, biosecurity, and O&M capacity are in place (Garrido-Baserba et al., 2024; Issahaku et al., 2024).

2.3.2 Composting

To inform the selection of decentralised organic-waste treatment methods, Table 3 contrasts bokashi (anaerobic fermentation) with conventional aerobic composting across operational, bio-sanitary, and regulatory dimensions.

Table 3: Anaerobic vs aerobic composting

Feature	Anaerobic fermentation	Aerobic composting
Acceptable inputs	Tolerates most kitchen scraps, including cooked food, small amounts of meat and dairy, because the process is closed and acidifies the mass.	Best practice limits home piles to plant residues; meat/dairy is discouraged due to pests and odours.
Process conditions	Airtight container; lactic acid fermentation inoculated with bokashi bran; low-oxygen, low-pH environment.	Aerobic biodegradation in piles/bins requires adequate oxygen, 50-60% moisture, and a C: N ratio of 25-30:1 to sustain thermophilic phases.
Cycle time	2 weeks of active fermentation, followed by in-soil maturation of the pre-compost.	Weeks to months, depending on method (hot/thermophilic vs cold), feedstock, and turning frequency.
Equipment & inputs	Sealed bin with drain and fermented inoculant (bokashi bran).	Low-tech bins or windrows; no specialised inputs beyond bulking agents/browns.

Odour & vectors	Very low odour; a closed system reduces insect and rodent infestations.	Well-managed piles are acceptable; mismanagement (high food waste, poor aeration) increases odour and vector populations.
Pathogen control	Acidification and exclusion of air limit putrefaction; the product must be matured in soil before planting.	Thermophilic composting that meets time-temperature-turning standards achieves verified pathogen reduction.
Regulatory assurance	Best treated as pre-compost requiring soil incorporation.	Thermophilic methods provide auditable food-safety assurance for farm use.
Process control	Simple operations (layering, compacting, inoculant dosing, periodic leachate draining).	Requires monitoring/management of C: N, moisture, porosity, and aeration; turning or forced aeration to avoid anaerobic pockets.
Emissions profile	Minimal odour/gas release during sealed fermentation; leachate must be managed.	Well-aerated hot composting limits odours; poor aeration elevates odour and can generate unwanted anaerobic by-products.
Output characteristics	Fermented “pre-compost” with high moisture and low pH; after soil maturation, it contributes organic matter and microbial activity.	Stable, humified compost that improves soil structure, water-holding capacity and nutrient cycling.
Best-fit context	Space-constrained or indoor settings; kitchens and lodges seeking to handle diverse food scraps with minimal nuisance.	Gardens, farms and facilities able to allocate space and labour for managed piles/windrows and seeking a soil amendment.

From an operational perspective, bokashi’s closed, acidifying process confers two clear advantages for mixed post-consumer food waste: (1) it suppresses odours and vectors, and (2) it tolerates materials, e.g. cooked food, small amounts of meat/dairy that are problematic in household aerobic systems (Fox and Tucker, 2025). Aerobic composting depends on a disciplined process: adequate porosity, moisture, and oxygen to sustain a thermophilic phase, typically with a C: N ratio of 25-30:1 and moisture of 50-60% (Oshins et al., 2022). Where these controls fail, odours and vectors rise, and anaerobic pockets can form, hurting process performance and community acceptance (Oshins et al., 2022).

The infrastructure and resource profiles are also different. Bokashi needs a sealed container and a microbial inoculant, but once it is up and running, it does not take up much space or time (Fox and Tucker, 2025). Aerobic composting can be done on a small scale with simple tools, but it requires turning or aerating every so often, and the feedstock must be well mixed. This is an acceptable trade-off when land and labour are available (Cromell, 2010).

2.3.3 Closed-loop nutrient management

Closed-loop nutrient management refers to the reuse of organic matter (compost, manure, digestate) to replenish soil fertility, reduce chemical input use, and enhance long-term sustainability. It aims to minimise nutrient leakage and maximise recovery within the farm boundary (Gartmann et al., 2023).

On-farm composting transforms organic residues into biologically active compost, enhancing microbial diversity and plant nutrient uptake (van der Velden et al., 2022). Kitchen waste compost has been shown to improve lettuce yield and post-harvest nutritional quality by increasing organic matter, potassium, and available phosphorus (de Paula et al., 2021).

2.3.4 Integration of livestock (Pigs, Chickens)

Livestock integration into Circular Economy (CE) agricultural systems offers a sustainable approach by utilising food waste as feed and producing nutrient-rich manure, thereby reducing feed costs, supporting waste reduction, and enhancing nutrient cycling. Pigs and chickens are well-suited for this role due to their omnivorous diets, which allow them to consume a diverse range of organic waste, including kitchen scraps and agricultural by-products. This mirrors practices in mixed farming systems, where livestock convert non-human-edible biomass, such as crop residues, into valuable outputs, minimising waste and improving resource efficiency (Swanepoel and Smit, 2025).

For instance, Italy processes agricultural waste into pig and poultry feed, reducing the need for imported feed and helping the environment by keeping waste out of landfills (Demichelis et al., 2025). In the Western Cape of South Africa, integrated crop-livestock systems use manure from grazing animals to recycle nutrients back into croplands. This can reduce synthetic fertiliser use by up to 30% in some cases (Swanepoel et al., 2015). Using this idea, pigs and chickens could be kept in controlled systems, such as mobile pens or rotational foraging on cover crops, to produce manure that improves soil fertility while also removing waste from conservation areas or ecotourism sites.

However, successful integration requires careful management. High stocking densities can negate benefits by increasing greenhouse gas (GHG) emissions and soil degradation (Matthews, 2023), necessitating optimised stocking rates and regular monitoring. The difficulty of managing mixed systems, such as feed supply and waste handling, can also be lessened by working together and training stakeholders, as shown in regional conservation agriculture projects (Swanepoel and Smit, 2025). These examples indicate that incorporating pigs and chickens into

conservation-oriented CE systems, such as private protected areas (PPAs), may improve resilience and sustainability, contingent upon the consideration of local conditions and trade-offs.

2.3.5 Management and safety considerations

In South Africa, using food waste as animal feed can be dangerous because it can spread pathogens, such as Salmonella and Clostridium, that can make both animals and people sick. In the European Union, all food waste must be heated (Salemdeeb et al., 2017). In South Africa, on the other hand, there is no such requirement. Instead, the country relies on broader safety standards. The Department of Agriculture, Land Reform, and Rural Development (DALRRD) is in charge of enforcing the Fertilisers, Farm Feeds, Agricultural Remedies, and Stock Remedies Act, 1947 (Act No. 36 of 1984). This law requires that all animal feed, including waste-derived feed, be free of harmful substances and pathogens. The Foodstuffs, Cosmetics and Disinfectants Act of 1972 (FCD Act) makes sure that any food waste used as feed does not pose a risk to people who eat it later. This aligns with the National Health Act of 2003, which emphasises safety and cleanliness throughout the food chain. The Meat Safety Act of 2000 sets hygiene standards for slaughter, which affects feed safety by regulating livestock health. In practice, South African operators frequently utilise Codex good-feeding principles as a benchmark (Codex Alimentarius Commission, 2004; FAO and IFIF, 2020).

2.3.6 Best practices

Integrated systems that use food waste to feed pigs and chickens must comply with South African health regulations and employ robust pathogen control measures, such as controlled fermentation or thermal treatment, to prevent contamination of food chains. The Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act, 1947 sets standards for safe feed production. However, because heat treatment is not required, farmers must take the initiative to follow best practices. Fermentation can lower the number of pathogens while making nutrients more available. This is supported by evidence that it works well for waste management (Chojnacka et al., 2024). The National Health Act of 2003 and the FCD Act emphasise cleanliness and safety by requiring regular testing of feed inputs.

To keep the environment safe, it is essential to monitor nutrient inflows and outflows. This way, manure from animals that eat treated waste can improve soil without introducing pathogens. The NEMWA (2008) encourages waste diversion, but it does not provide clear instructions on how to keep animal feed safe. Working with DALRRD and municipal health services to set up monitoring protocols should be part of best practices. In conservation settings such as PPA's, integrating these measures may improve sustainability; however, feasibility depends on the availability of cost-effective treatment technologies and training.

2.4 Industrial engineering attributes, enablers and barriers in circular agriculture systems

This study utilises established production-systems scholarship to adapt operations management principles for process design and systems integration (Slack and Brandon-Jones, 2019). The methodology implements Lean principles of waste elimination and value stream optimisation to improve process flow, as elucidated by Womack and Jones (1997). Additionally, it incorporates variability and capacity control strategies to ensure safety and achieve robust operational performance, as outlined by Hopp and Spearman (2011). These sources provide the quantitative and systems-based toolkit for designing closed-loop agri-food operations that operate under regulatory, economic, and ecological constraints.

Table 4 below synthesises IE-relevant attributes, enablers, and barriers from selected circular interventions discussed in Sections 2.1-2.3:

Table 4 IE-relevant attributes, enablers, and barriers

Circular Intervention	IE Attributes	Enablers	Barriers
Food waste-to-feed (pigs/chickens)	Process control, flow modelling, quality assurance, compliance mapping	Existing waste streams, fermentation tech, animal integration	Lack of mandatory regulation, biological risk, and farmer training gap
On-site composting and bokashi	Process timing, input/output balancing (MFA), system layout	Low-tech options; nutrient recycling; positive soil impacts	Need for space and training; inconsistent feedstock quality; poor waste sorting systems
Fermentation of waste for feed	Bioprocess optimisation, quality tracking	Pathogen reduction; improved digestibility; scientific validation	Infrastructure cost, anaerobic condition control, and knowledge gap among conservation staff
Waste reuse systems	Integrated system design, feedback loop control, VSM for nutrient and water flows	High productivity; closed-loop nutrient cycling; modular scalability	Energy demands; initial capital outlay
Material Flow Analysis (MFA)	Quantitative flow tracking, resource efficiency modelling	Standardised tool; adaptable to conservation settings; visualisation aids system decisions	Requires baseline data; modelling skills

Value Stream Mapping (VSM)	Process mapping, non-value activity identification, Lean redesign	Identify bottlenecks and waste hotspots Redesign processes to cut transport and disposal inefficiencies Support closed-loop reintegration of outputs Achieve Lean-green synergy via data-driven IE optimisation	Needs training in Lean systems; less developed for non-industrial contexts
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2.5 Arid and semi-arid classification

Arid and semi-arid regions are defined by low and erratic annual precipitation, high evapotranspiration, and frequent drought events (FAO, 2020; UNEP, 2016). The Köppen-Geiger climate classification distinguishes arid and semi-arid climates based on temperature and precipitation thresholds (Beck et al., 2018). These kinds of climates are found in large parts of North Africa, the Middle East, Central Asia, western India, and central Australia.

Most of Namibia and Botswana, the Kalahari region, large parts of South Africa (like the Northern Cape and parts of the Western Cape), southern Zimbabwe, the lowland areas of Ethiopia, Somalia, and eastern Kenya are all arid or semi-arid zones in sub-Saharan Africa (UNEP, 2016; FAO, 2020). These areas have a lot in common when it comes to problems: the soil is not very fertile, the land is likely to get worse, and there isn't enough water at certain times of year or year-round. These limitations directly influence agricultural practices and resource management strategies, rendering them highly relevant to research on resource-efficient, circular-economy-based agricultural systems (Adelodun et al., 2024; Urugo et al., 2024).

CHAPTER 3

3 Research methodology

3.1 Research design: Design Science Research (DSR)

A Design Science Research (DSR) framework was employed to develop and rigorously evaluate an artefact: a theoretical circular-economy (CE) model for the on-site conversion of organic waste into valuable resources within an eco-tourism reserve. This approach was further refined by incorporating procedural enhancements suggested by Dresch et al. (2014), which highlight explicit problem classifications and transferable design principles, as well as by adopting multi-level (echeloned) perspectives on socio-technical systems as described by Tuunanen et al. (2024). For clarity, the DSR methodology is organised into six iterative activities as delineated by Peffers et al. (2007):

1. **Problem identification and motivation:** the practical problem and its significance are articulated.
2. **Objectives of a solution:** desired properties and performance objectives of the artefact are specified.
3. **Design and development:** the artefact is conceived and built.
4. **Demonstration:** the artefact is exercised in a relevant setting to show feasibility.
5. **Evaluation:** the artefact's quality and utility are assessed against the stated objectives using appropriate criteria.
6. **Communication:** the problem, artefact, and results are reported to scholarly and practitioner audiences.

3.2 Phase structure and mapping to chapters

The DSR cycle was operationalised as five phases to anchor sequencing and evidence flow. The phases are defined in Table 5.

Table 5: Alignment between research objectives and methodology

Phase	Objective	Research Method	Thesis Chapter
Phase 0 - Literature survey (DSR 1-2)	Determine the literature on general concepts such as circular economy principles, applicable Industrial Engineering methodologies, organic waste management in conservation and ecotourism settings, and circular agriculture practices.	Narrative literature review	Chapter 2
Phase 1 - Identification of (DSR 3)	Determine the technical, environmental, legal, and operational aspects of a circular economy model by means of a scoping review of academic literature and legal documents.	Scoping review of academic and legal literature	Chapter 4 - 5
Phase 2 – Design (DSR 3-4)	Design a theoretical circular economy model, mapping process flows, material exchanges, and key performance indicators.	Industrial engineering modelling tools, e.g., MFA and VSM.	Chapter 6-7
Phase 3 - Verification (DSR 5)	Verify that the conceptual model adheres to all identified technical, environmental, legal, and operational.	Criteria compliance assessment and SEQUAL	Chapter 8
Phase 4 – Validation (DSR 5)	Validate the conceptual model through scenario analysis and sensitivity testing, using real-world data as the baseline scenario.	Scenario analysis and sensitivity testing (Maier et al., 2021)	Chapter 9

- **Phase 0 - Literature survey (DSR 1-2):** A narrative review of CE/Industrial Engineering background was undertaken.
- **Phase 1 - Requirement identification (DSR 3):** a scoping review and legal cross-walk were used to generate coded registers (LIT) and (LEG).
- **Phase 2 - Design and development (DSR 3-4):** a conceptual CE model, boundary conditions, specifications, flows, and KPIs were produced.
- **Phase 3 - Verification (DSR 5):** SEQUAL-based checks and a compliance mapping to (DR-LIT/LEG) were conducted.
- **Phase 4 - Validation (DSR 5):** scenario analysis and sensitivity testing were performed against KPI thresholds (Chapter 9).

3.3 Methods and roles

Four complementary methodological techniques were employed in alignment with the DSR cycle.

3.3.1 Scoping review methodology

A scoping review was conducted to characterise the evidentiary landscape where methods are heterogeneous, and concepts diffuse, typical of CE in agri-food and conservation contexts. The

Arksey and O'Malley (2005) framework, as extended by Levac et al. (2010), was followed, with reporting aligned to PRISMA-ScR (Tricco et al., 2018). The review (Phase 1) was used to assemble a portfolio of applicable CE practices and components, normalise and code recommendations as (DR/RC-LIT-xxx), capture enabling conditions and constraints as (EN/CN-LIT-xxx), and identify indicators aligned to the Circularity Gap Report (2025).

3.3.2 Semiotic Quality Framework (SEQUAL)

The Semiotic Quality Framework (SEQUAL), selected for assessing a circular economy model, evaluates model quality using semiotic dimensions. Developed by Lindland, Sindre, and Sølvsberg (1994) and expanded by Krogstie et al. (2006), (Krogstie, 2015). Krogstie (2016) further tailored SEQUAL for domain-specific, goal-oriented models, emphasising evaluation relative to goals and stakeholders. This study uses SEQUAL to assess internal quality across various dimensions, referencing and Material Flow Analysis diagrams. SEQUAL aligns with SEQUAL-GEN and Krogstie's goal-set alignment principle, ensuring that verification matches the artefact's purpose. It integrates syntactic, semantic, pragmatic, and social qualities, focusing on reality representation, understanding, and insights. For the circular economy model, SEQUAL checks consistency, completeness, and practical adequacy, ensuring clarity, actionability, and alignment with sustainable waste valorisation goals. The framework is implemented explicitly during Phase 3 (Verification) of the research methodology to assess the coherence and communicative efficacy of the conceptual CE model.

3.3.3 Scenario analysis, regression validation, and statistical process control

Three methodological approaches are pivotal in ensuring the rigour of model validation: linear regression, scenario analysis, and statistical process control (SPC). Linear regression is employed to evaluate model validity by analysing relationships among variables, thereby confirming the model's concordance with empirical data. (Snee, 1977). Scenario analysis is used to assess the model's robustness by testing its performance across a range of potential conditions, thereby ensuring its resilience in the face of extremes (Amer et al., 2013). Statistical process control serves as a tool for continuous monitoring, verifying process stability by distinguishing between random variation and significant deviations from the norm (Alcantara et al., 2017). Collectively, these methodologies provide a thorough framework for model validation, thereby establishing statistical credibility, contextual robustness, and dynamic stability, all grounded in well-established scientific methods.

3.3.4 Modelling support and performance tracking

Material Flow Analysis (MFA) was used to close mass balances and quantify flows between nodes. At the same time, Value Stream Mapping (VSM/SVSM) was applied to reveal bottlenecks, queueing, and non-value-adding activities. Indicator definitions followed the Circularity Gap Report (2025) and the node-specific quality gates extracted from the scoping review. These tools were used during design and later to support verification/validation.

Data, traceability, and coding governance

Traceability was enforced through compact evidence codes embedded in the text. Literature-derived design evidence and indicators were recorded as (DR/RC/EN/CN-LIT-xxx), legal and policy obligations were recorded as (DR/RC-LEG-xxx), and empirical, site-specific statements will be created as (DR/RC-EMP-xxx) during application and testing. Each design decision was referenced to at least one code; each verification item was tied to a specific artefact (e.g. SOP, log, specification, permit), thereby enabling auditable pass/gap judgements and coherent propagation of assumptions into validation scenarios.

This clarifies that Phase 0 implements DSR 1 and 2 (problem identification and objectives) in chapters 1 and 2, Phase 1 implements DSR 3 (design and development) in chapters 4 and 5, Phase 2 implements DSR 3-4 which now includes demonstration of the model in the Reserve's context, Phase 3 implements DSR 5 (evaluation) which verifies the model against design and legal requirements. At the same time, Phase 4 also implements DSR 5, which tests the model against realistic scenarios as a validation.

This study applied a systems thinking perspective, which emphasises the interdependence of components, feedback loops, and emergent properties. Systems thinking provided the lens through which organic waste was not examined in isolation, but as part of a wider metabolism connecting food preparation, livestock, horticulture, and resource recovery. This paradigm guided the extraction of (Chapter 4) and the structuring of the conceptual model (Chapter 6).

3.4 Phase 1: Scoping review

This phase establishes the empirical foundation for the conceptual design of the circular economy model by systematically gathering, mapping, and synthesising evidence from academic, policy, and industry sources. A structured scoping review methodology is utilised to ascertain and essential system parameters relevant to circular models in conservation-oriented agricultural systems.

3.4.1 Step 1: Define the research question

The PCC (Population-Concept-Context) framework is used to develop a guiding research question that narrows the review to examine how the circular economy can be applied in agri-food systems, waste management, and conservation or ecotourism settings (Arksey and O'Malley, 2005; Levac et al., 2010).

3.4.2 Step 2: Identify and select relevant studies

A systematic search strategy is implemented across scholarly databases, including Scopus and Google Scholar, as well as grey literature sources such as governmental reports, policy briefs, and publications from non-governmental organisations. Boolean search logic is employed with specific keywords such as "circular economy," "organic waste," "agriculture," "ecotourism," "food systems," and "South Africa." Inclusion and exclusion criteria are strictly defined, encompassing parameters such as a temporal range from 2015 to 2025, studies published in English, and those pertinent to circular design or system implementation, as referenced by Grant and Booth (2009) and Peters et al. (2015).

3.4.3 Step 3: Synthesise key findings and system requirements

Descriptive and thematic analyses are used to organise the literature in a structured way.

Key deliverables include:

- A categorised list of circular interventions that can be used in ecotourism-based agri-food systems
- Design needs that are both general and specific to the situation
- Necessary operational parameters for designated subsystems (e.g., bokashi bins, livestock feeding, hydroponics)
- System-wide considerations for implementation in semi-arid, conservation-oriented areas (Adelodun et al., 2024; Roos et al., 2022; Chitaka and Schenck, 2022).

3.4.4 Step 4: Validate findings with legislative and policy sources

The National Waste Management Strategy (2020), the South African Bioeconomy Strategy (DST, 2013), and other relevant provincial or local environmental plans are all used to check the academic findings against. This validation guarantees that the recognised system design components are not only substantiated by evidence but also effectively aligned with national objectives for waste reduction, resource recovery, and biodiversity conservation (DEFF, 2020; DST, 2013).

3.5 Phase 2: Design a theoretical circular economy model

Phase 2 translates the requirements set in Phases 0-1 into a coherent, theoretically grounded circular-economy (CE) artefact tailored for a remote ecotourism reserve in semi-arid Southern Africa. Within the DSR logic, this is the design & development activity: specifying the system boundary and granularity; decompose the system into interacting subsystems (waste-generation nodes, processing units such as bokashi, anaerobic digestion, black soldier fly larvae and composting, reuse sinks in livestock and horticulture, and residuals management); and define the integration mechanisms that close the loops (material and information flows, inventory buffers, control logic and operating rules). All design decisions are constrained by the documented legal, safety, environmental, and operational requirements, with assumptions, data sources, and decision criteria recorded to enable Phase 3: verification.

3.5.1 Step 1: Formalising system requirements from the literature

System requirements are not inferred arbitrarily but is explicitly extracted from peer-reviewed and legal literature (Phase 1). Sources are analysed to derive criteria across four functional dimensions:

- 1. System functions** (e.g. waste valorisation, closed-loop nutrient cycling)
- 2. Performance expectations** (e.g. resource-use efficiency)
- 3. Process attributes** (e.g. modularity, scalability, regulatory compliance)
- 4. Circularity principles** (e.g. renewability, cascading use, feedback loops)

These criteria are tabulated and used to structure the model's design logic, ensuring traceability from the literature to the system components. For instance, the CGR (2025) guidelines on circular biomass flows are formalised as model constraints, requiring each element to demonstrate at least one of: minimal ecological impact, renewable material sourcing, cascading use, or closed nutrient cycling.

3.5.2 Step 2: Component identification:

Key functional blocks such as livestock feeding, vegetable cultivation, bokashi composting, and consumption will be defined based on CE practices documented in the literature (Sekabira et al., 2024). Biomass flows are designed in accordance with CGR's (2025) recommendations, which emphasise carbon neutrality, nutrient cycling, and ecological integrity. The four criteria for circular biomass flows proposed by CGR (2025), minimising ecological impact, ensuring renewability, cascading use, and closing nutrient cycles, are clearly built into the conceptual model. For example, bokashi composting is modelled not merely as an end-of-pipe waste solution but as a

regenerative loop that returns carbon and nutrients to local soils. Likewise, livestock-feeding pathways are designed to maximise cascading value.

3.5.3 Step 3: System mapping and boundary definition:

Employing the systems-thinking methodology, which is extensively embraced in the scholarly discourse on Circular Economy (CE), this study aims to delineate the pathways of organic waste, nutrients, and food products. This methodological framework is based on the research by Chitaka and Schenck (2022), which underscores the critical need to identify sector-specific interconnections and feedback mechanisms.

3.5.4 Step 4: Model visualisation:

The model will be depicted via a functional block diagram, illustrating circular interactions among subsystems (Lombardi et al., 2021).

3.6 Phase 3: Verification

The verification phase primarily assesses the internal quality and structural integrity of the conceptual circular economy model before its contextual adaptation and subsequent validation. Within the realm of Design Science Research, this phase is critical to ensuring that the artefact logically meets the specified requirements before field testing. The SEQUAL framework is utilised to authenticate the conceptual model and its associated artefacts. These artefacts include the system architecture, Material Flow Analysis diagrams, and the coding traceability matrix. SEQUAL is an ex ante verification tool designed to evaluate the model's internal coherence, interpretability, and communicative quality (Venable et al., 2016).

The transformation of each SEQUAL dimension into verification inquiries is conducted in accordance with the model's architectural framework and the stakeholder context at The Reserve. Syntactic quality assurance focuses on assessing the model's internal coherence with respect to the applied modelling language and ensuring diagrammatic consistency across the material flow analysis components. Assessment of semantic quality involves comparing model relations and flows with empirical data extracted from the pilot system, including measurements of waste quantities, conversion ratios, and process linkages. This assessment aims to validate an accurate representation of real-world conditions. Pragmatic quality is evaluated through stakeholder engagement sessions and expert reviews, which verify whether the model's notation, terminology, and logic are comprehensible and operationally relevant.

The assessment of social and organisational quality dimensions is conducted by evaluating the degree of consensus among researchers, technical personnel, and management regarding the

model's efficacy in facilitating coordination, learning, and strategic alignment. This multi-perspective analysis ensures that the artefact not only adheres to formal modelling standards but also effectively communicates meaning and usability to its target audience. The verification process, therefore, involves determining whether the conceptual model and its associated artefacts collectively demonstrate the consistency, completeness, and contextual adequacy necessary to support the subsequent validation phase and inform circular waste-management decision-making at The Reserve.

3.7 Phase 4: Validate conceptual model

The validation stage is designed to assess the conceptual model's efficacy and resilience for a circular economy through a comprehensive validation program integrating statistical and scenario-based methodologies. This approach adheres to the guidelines proposed in the model-based decision-support literature (Maier et al., 2021). Thereby avoiding the necessity for complete implementation by leveraging empirical pilot data alongside simulated scenarios. This enables an evaluation of system performance across both realistic and hypothetical operational conditions.

Validation uses three synergistic techniques: bootstrap regression, scenario analysis, and statistical process control (SPC), for a comprehensive evaluation of the model's validity.

Linear regression serves to verify a model's internal coherence by quantitatively analysing relationships among key variables derived from pilot-scale data. As noted by Snee (1977), this corroborates the model's coherence by aligning the predicted relationships with theoretical expectations. Diagnostics, such as the coefficient of determination (R^2), residual analysis, and assessments of the slope and intercept, are employed to ascertain whether the observed responses are consistent with the model's assumptions. Jan and Shieh (2019) further assert that this process enhances scientific credibility by affirming the stability of parameters and the reliability of predictions, which are essential for extrapolation to theoretical scales.

Scenario analysis assesses the model's robustness under different conditions. As per Amer et al. (2013) and Maier et al. (2021), each scenario represents a consistent system configuration that reflects the diversity observed in pilot testing.

The pilot dataset, spanning two 13-week operational seasons, analysed waste patterns linked to guest occupancy, staff activity, and kitchen operations. Data were normalised by weekly waste mass and source. Analysis identified recurring week-types via statistical classification: Low-load weeks (<25th percentile) during off-peak times; Average-load weeks (25th-95th percentile) for normal operations; High-load weeks (95th percentile) indicating increased activity; and Peak weeks (>97th percentile) during special events or full occupancy.

The week-type categorisations were grouped into three operational clusters: low-load, average-load, and peak-load, covering the full range of variability in the six-month data. Each cluster includes varied weeks from both seasons, preserving the natural frequency of each type. Low-load contains weeks with below-average and off-peak conditions, average-load includes mid-range to 95th percentile weeks, and peak-load consists of the highest intensity weeks.

Applying clustering to pilot data grounds validation scenarios in real operational regimes rather than theoretical assumptions. This ensures simulated conditions for regression, scenario testing, and SPC monitoring accurately reflect the true seasonal variability and randomness in organic waste generation at the reserve.

The three clustered scenarios are evaluated using the Chapter 2 KPIs: waste-diversion (%), waste-conversion (%), resource-efficiency (kg/kg), secondary-material substitution (%), controlled-disposal (%), reserve-level circularity (%), and System Performance Index (SPI, 0-100).

To assess the statistical stability of model outputs, Statistical Process Control (SPC) methodologies are applied across iterative simulations for each clustered scenario. Employing control-chart methodologies, including $\bar{X}$ -S and p-charts contingent on data typology, enables determining whether forecasted outcomes remain within predefined control thresholds. Alcantara et al. (2017) demonstrated that Shewhart-type control charts effectively identify deviations in anaerobic digestion processes. In contrast, Cinar et al. (2022) showed that integrating control charts into Lean Six Sigma frameworks enhances process reliability by distinguishing stochastic fluctuations from structural irregularities. In alignment with Shewhart's rules as elucidated by Montgomery's (2020) observations that surpass the three-sigma control boundaries, sequences comprising eight or more consecutive observations on a single side of the central line, trends consisting of six or more successive observations exhibiting an increase or decrease, or the presence of cyclical patterns, shall be construed as indicators of assignable (special) causes rather than stochastic variation. Such out-of-control observations will be scrutinised to diagnose underlying process disturbances, data anomalies, or shifts in operational regimes within the context of the modelled scenarios.

Integration of regression validation, cluster-scenario analysis, and SPC monitoring provides a comprehensive assessment of the conceptual model. Linear regression ensures logical soundness, clustered scenarios test robustness under real conditions, and SPC ensures statistical control and stability. This framework ensures that the circular-economy model is empirically derived, statistically robust, and operationally credible for implementation at the reserve scale.

CHAPTER 4

Circular opportunities for food waste valorisation in Southern African eco-tourism reserves: A Scoping review

Gideon de Wet, Rojanette Coetzee, Noluthando Noxolo Aruwajoye and Meelan Roopa

This study examines the challenge of managing organic waste in ecotourism landscapes, where biodiversity protection conflicts with tourism's resource demands. Empirical guidance on circular economy use in such remote, sensitive settings is limited. Using a structured scoping review based on a six-stage evidence-mapping framework and the Population-Concept-Context model, the study identifies and classifies circular strategies for organic-waste management in Southern African eco-tourism contexts. A functional block diagram maps core resource flows and treatment pathways in circular organic-waste systems, providing a framework for evaluating interventions. The review outlines modular approaches focused on waste valorisation, nutrient recovery, and regenerative loop closure. Successful implementation depends on behavioural participation, institutional governance, context-appropriate technologies, and phased deployment within financial and infrastructural limits. The synthesis defines system requirements, enabling conditions, and constraints that support the design of decentralised circular waste-valorisation models for eco-tourism environments.

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4.1 Chapter Orientation

The work portrayed in this chapter/article forms part of the identification of phase of the DSR methodology.

Table 6 Chapter 4 (Scoping Review) orientation

Phase	Objective	Research Method	Thesis Chapter
Phase 1 - Identification of (DSR 3)	Determine the technical, environmental, legal, and operational for a circular economy model by means of a scoping review of academic literature and legal documents.	Scoping review of academic and legal literature	Chapter 4 - 5

4.2 Research Question

The research question addressed by this chapter is as follows:

- *What circular economy strategies, system components, and system requirements have been proposed or implemented to manage organic waste in agricultural and tourism-linked systems, particularly in conservation or remote contexts?*

Circular opportunities for food waste valorisation in Southern African eco-tourism reserves: A Scoping review

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ABSTRACT

The management of organic waste in ecotourism zones highlights a paradox between the preservation of biodiversity and the resource-intensive demands of tourism. Empirical evidence showcasing circular economy models customised for such remote and ecologically sensitive environments remains limited. This study lays the groundwork for a circular economy model applicable to Southern African ecotourism through a structured scoping review, utilising the established six-stage framework for evidence mapping and the Population-Concept-Context framework. A functional block diagram was constructed to illustrate the fundamental resource flows and treatment pathways integral to circular organic waste systems. This serves as a conceptual framework categorising intervention identified in the scholarly literature. The synthesis pinpoints a modular array of circular economy strategies focusing on waste valorisation, nutrient recovery, and the closure of regenerative loops. The success of implementation hinges on behavioural participation, effective institutional governance, and the alignment of technology with contextual needs, facilitated by a phased deployment approach under financial and infrastructural limitations. The review generates a codified registry of systems requirements, enabling factors, and constraints, which constitutes the empirical foundation for decentralised circular waste valorisation systems within ecotourism environments.

Keywords: circular economy, food waste, protected areas, ecotourism, semi-arid, Southern Africa.

1 Introduction

Protected areas within South Africa play an important role in the preservation of biodiversity and the maintenance of ecological integrity. In accordance with the stipulations set forth by the National Environmental Management: Protected Areas Act (NEMPAA), these areas are required to sustain ecological processes and safeguard species that are under threat while simultaneously promoting sustainable development and tourism. This dual mandate presents a paradoxical challenge: the pursuit of economic benefits through tourism activities often results in the degradation of the very environments these areas are intended to protect. Ecotourism reserves are associated with the generation of substantial quantities of organic waste, which necessitates management through disposal methods that are not only financially burdensome but also emit significant greenhouse gases, thereby undermining the fundamental sustainability objectives (Mukwevho et al., 2024). This challenge is fundamentally a systems-design problem that necessitates the integrated coordination of material flows, operational processes, infrastructure constraints, and resource-efficiency requirements. Taken together, these characteristics position the problem squarely within the analytical domain of the engineering sciences, most notably industrial engineering, which is concerned with the modelling, quantitative analysis, and optimisation of complex, resource-intensive socio-technical systems.

Globally, the phenomenon of food waste constitutes a systemic challenge within agri-food systems, with an estimated one-third of all food produced, amounting to approximately 1.3 billion tonnes per annum, being either lost or discarded (Adedeji, 2022). This loss represents a significant dissipation of the embedded resources, including water, energy, nutrients, and economic value (Adelodun et al., 2024). Such waste streams are intrinsically linked to greenhouse gas emissions, soil nutrient depletion, and the degradation of ecosystem services, particularly when decomposition occurs unmanaged in landfill environments (Urugo et al., 2024). In South Africa, the National Department of Environment, Forestry and Fisheries (2020) established a national objective to reduce landfill dependency by 40% within five years. Despite this, recent evaluations indicate that the nation is significantly distant from reaching this goal. Current research indicates that South Africa generates over 125 million tonnes of solid waste per annum, with the majority still disposed of in landfills (Research And Markets, 2024). Additionally, investigative reports have pointed out that comprehensive data on national waste diversion rates are lacking, suggesting that the actual levels of waste recovery are likely much lower than those reported in official statistics (Kretzmann, 2024). However, empirical evaluations reveal persistent structural and operational impediments that hinder progress. Chitaka and Schenck (2022) highlight that organic residues remain substantially underutilised due to limited treatment

capacity, fragmented value chains, and insufficient investment in decentralised waste-valorisation technologies.

Within protected areas, the constraints imposed at the national level are exacerbated. The economies reliant on ecotourism are predicated on the provision of superior visitor experiences and the maintenance of ecological integrity. However, the prevalent reliance on landfill disposal is at odds with conservation imperatives and introduces considerable logistical and environmental risks, particularly in remote reserves that suffer from inadequate infrastructure. Municipal authorities, who bear the legal obligation for waste management services, frequently encounter shortages in personnel, equipment, and financial resources necessary to ensure effective waste collection and processing in rural areas and regions associated with conservation. This often results in services that are inconsistent or ineffective, as noted by Mukwevho et al. (2024). Consequently, managers of protected areas find themselves in a paradoxical situation: they are charged with the stewardship of biodiversity while simultaneously being entrenched in linear waste management systems that externalise ecological costs, increase emissions, and compromise long-term sustainability objectives.

Waste composition worsens the problem. Dell'Orto and Trois (2024) state that organic matter like food scraps and yard trimmings makes up over 40% of municipal waste in South Africa. Internationally, the U.S. Environmental Protection Agency (EPA) (2023) notes about 24% of landfill content is food waste, and more than half is organic materials when including yard and wood residues. These figures highlight organic waste's dominance in global municipal waste streams. Transporting such materials long distances increases the carbon footprint of ecotourism and heightens environmental risks. Methane emissions from decomposing organic matter and leachate contamination threaten soil and groundwater. In remote conservation areas, these issues are worsened by limited budgets and staffing shortages, as noted by Mukwevho et al. (2024).

At the governance level, existing environmental methodologies have not adequately evolved to align with current ecological realities. Retief et al. (2025) contend that the practice of Environmental Impact Assessment (EIA) within protected areas continues to exhibit an anthropocentric and linear paradigm. Although EIAs are proficient in identifying environmental impacts, they seldom facilitate the incorporation of feedback mechanisms, resource recovery processes, or regenerative strategies. The prevailing treatment of waste as a terminal product, rather than as a potential resource, limits the prospects for implementing circular resource management frameworks.

The challenge further extends to the broader development agenda articulated in Sustainable Development Goal (SDG) 2 (Zero Hunger). SDG 2 explicitly seeks to “end hunger, achieve food security and improved nutrition and promote sustainable agriculture” (United Nations, 2023). Empirical evidence from circular agricultural systems in sub-Saharan Africa indicates that nutrient-recovery practices reduce dependence on external inputs, enhance soil fertility, and increase the resilience of local food systems (Nkansah-Dwamena, 2024). Through the facilitation of composting, biofertiliser production, and feed-substitution pathways, circular resource-use practices thereby advance the ecological and food-security objectives embedded in SDG 2, particularly in remote conservation landscapes where access to fresh produce and the reliability of supply chains remain constrained.

The circular-economy paradigm introduces a fundamentally distinct framework that diverges from the traditional "take-make-dispose" model. Instead, it aims to eliminate waste through design, prolong the lifecycle of materials, and rejuvenate natural systems (Ellen MacArthur Foundation, 2022). According to Adelodun et al. (2024), the integration of circular principles within agri-food systems can lead to a reduction in emissions and enhancement of nutrient cycling. Concurrently, Toplicean and Datcu (2024) highlight how circular bioeconomy practices interconnect sustainable agriculture with renewable energy and waste valorisation. These notions align with the eco-centric tenets proposed by Retief et al. (2025) for prospective environmental governance, which underscore stewardship, non-regression, and the intrinsic worth of ecosystems.

The problem identified in this study pertains to the management of organic waste within protected areas, which is currently characterised by linear, landfill-dependent practices. These practices are misaligned with conservation objectives, result in the unnecessary emission of greenhouse gases, and lead to the wastage of nutrient-dense biomass that could otherwise be utilised to enhance regenerative ecological processes.

However, the adoption of circular-economy strategies in conservation landscapes presents an avenue to harmonise the often conflicting goals of ecology and economy. The aim of this research is therefore to execute a Scoping Review with the purpose of systematically mapping, classifying, and synthesising existing interventions within the circular economy paradigm pertinent to the management of organic waste in the contexts of ecotourism and protected areas. This applied review, therefore, delineates current interventions within the circular economy relevant to organic waste management in eco-tourism and protected area scenarios. Through a systematic synthesis of both international and regional studies, it identifies the operational components, enabling strategies, and design parameters that could inform practical, context-sensitive circular models

tailored for Southern Africa. The resulting insights lay the groundwork for reconceptualising waste in protected areas, not as an unavoidable by-product of tourism, but as a renewable resource for maintaining ecological and economic resilience.

The article is organised as follows. Section 2 provides the Southern African context for research in the field of CE. Section 3 delineates the theoretical underpinnings, integrating circular economy theory, bioeconomy concepts, and environmental governance frameworks specific to protected areas. Section 4 details the methodological approach and the procedures for literature search and study selection. Section 5 reports the review results. Section 6 synthesises these results in relation to the existing body of knowledge and discusses design implications for decentralised circular waste management systems. Section 7 concludes by outlining key recommendations and priority areas for future research to further develop context-sensitive circular economy models in protected areas and ecotourism settings.

2 Southern African context

Research on the circular economy within the Southern African context remains relatively underexplored; however, it is progressively advancing through collaborative efforts led by institutions concentrating on waste valorisation, agri-food system resilience, and resource recovery. Academic inquiries associated with prominent South African institutions, including the University of Cape Town, North-West University, and the University of the Witwatersrand, have notably contributed to this burgeoning domain. Chitaka and Schenck (2022) detail the structural and policy limitations that obstruct the transition towards a circular bioeconomy, such as insufficient financial support and a lack of coordinated implementation frameworks within the National Waste Management Strategy. Furthering this discourse, Roos et al. (2023) accentuate the necessity for responsible waste governance in protected areas, suggesting beneficiation and recovery methodologies that resonate with circular economy principles, despite not being explicitly categorised as such. Investigations conducted in Zimbabwe (Dzawanda et al., 2023) and Botswana (Mathobela et al., 2023) similarly illustrate how small-scale enterprises and livestock systems can function as components of a circular economy when waste streams are effectively redirected back into productive channels. Cumulatively, these scholarly works articulate the regional dialogue on the circular economy through a lens of adaptive pragmatism, emphasising waste repurposing via low-capital, context-sensitive innovations as opposed to the technology-intensive solutions prevalent in developed regions.

Southern African research highlights the impact of local climatic variability, infrastructural limitations, and socio-economic disparities on the development of viable valorisation pathways. Mukwevho et al. (2024) and Dell'Orto and Trois (2024) demonstrate that decentralised

composting, co-digestion, and nutrient recovery systems exhibit greater resilience to governance and logistical challenges compared to centralised waste collection infrastructures. This regional corpus of evidence indicates a gradual transition from mere waste minimisation towards achieving material circularity, offering an empirical basis to model circular bioeconomy initiatives within conservation and ecotourism environments.

3 Theoretical imperatives

The theoretical framework of this review is grounded in three interconnected domains: (1) circular-economy theory, (2) bioeconomy and resource valorisation, and (3) conservation governance within protected areas. Each of these domains offers a perspective through which the systemic management of organic waste in eco-tourism settings can be theoretically conceptualised.

3.1. Circular economy

The concept of a circular economy (CE) is designed to rectify the inefficiencies inherent in the conventional "take-make-dispose" model through the promotion of resource efficiency and the minimisation of waste. The foundational work of Pearce and Turner (1989) established the initial principles of CE, which were subsequently expanded by the Ellen MacArthur Foundation (2022) into a comprehensive framework aimed at waste elimination, the retention of materials in continuous use, and the regeneration of natural ecosystems.

European policy initiatives in the 1990s incorporated these concepts, embedding the "3R" principle: Reduce, Reuse, Recycle into both economic and environmental strategies, thereby transitioning from a focus on waste management to a broader systems thinking approach. The work of Geissdoerfer et al. (2018) further elucidates the concept of Circular Supply Chains (CSCs), which are designed to close, slow, and narrow resource flows, thereby extending product lifespans and facilitating reuse and recovery.

The principles of industrial engineering complement CE by focusing on the design and enhancement of integrated systems, as discussed by Roopa et al. (2024), who underscore the importance of tools such as green supply chain management. Furthermore, CE theory reconceptualises organic waste as a renewable input, linking industrial efficiency with ecosystem restoration, and providing a pathway to regenerative development within conservation and agri-food sectors.

3.2. Bioeconomy and waste valorisation

The bioeconomy integrates the principles of the CE with biological resources, emphasising the transformation of biomass into value-added products such as biofertilizers, biogas, and feed ingredients (Adelodun et al., 2024). Toplicean and Datcu (2024) conceptualise the bioeconomy as a multidimensional framework encompassing renewable energy, sustainable agriculture, and environmental protection, with waste valorisation as its fundamental component. Within agri-food systems, innovative technologies such as black-soldier-fly larvae bioconversion (Mlambo et al., 2023), microbial fermentation, and struvite precipitation facilitate nutrient cycling and mitigate greenhouse gas emissions (Chandrasekaran et al., 2024).

These technological interventions in conservation landscapes promote a regenerative production model that interconnects food, feed, and fertiliser systems through feedback loops, thereby aligning with the Sustainable Development Goals aimed at decoupling economic growth from resource depletion and advancing climate change mitigation in food-system management (Adelodun et al., 2024).

3.3. Governance and environmental management in protected areas

Protected areas represent distinct governance regions where the ecological integrity imperative must be harmonised with economic activities. The National Environmental Management: Protected Areas Act 57 of 2003 is legislated to promote biodiversity conservation, sustainable utilisation of resources, and the provision of ecosystem services. Nevertheless, Retief et al. (2025) highlight that the management of these areas predominantly relies on anthropocentric and linear models, which primarily emphasise mitigation over regenerative practices. The integration of CE principles within management necessitates the development of novel governance frameworks that emphasise feedback mechanisms, resource recovery, and efficiency. Roos et al. (2023) emphasise the importance of responsible waste management within protected areas through strategies of recovery, minimisation, and beneficiation, in accordance with the environmental duty-of-care legislation in South Africa. The authors' emphasis on resource recovery and operational efficiency is consistent with the principles of a circular economy, which advocates for closed-loop material flows.

Collectively, these theoretical dimensions constitute the basis for examining the contextualisation of circular-bioeconomy strategies within eco-tourism reserves. The CE provides the systems architecture, while the bioeconomy offers the technological pathways necessary for resource transformation. Additionally, the governance of protected areas delineates the normative and legislative parameters. The interplay among these aspects forms the conceptual framework for the current scoping review, which aims to identify enabling mechanisms, operational constraints,

and transferable systems requirements pertinent to sustainable waste-valorisation models in Southern Africa.

4 Methodology

This scoping review adopted the methodological framework proposed by Arksey and O'malley (2005), which provides a systematic approach to the mapping of research across various fields, with a particular emphasis on the synthesis of themes and the identification of research gaps rather than the aggregation of effect sizes. Enhancements suggested by Levac et al. (2010) were incorporated to improve clarity, stakeholder engagement, and the robustness of the analysis.

The type of review was categorised using the typology developed by Grant and Booth (2009) to ensure alignment with established research methodologies and to maintain transparency. The PCC (Population, Concept, and Context) model was utilised to precisely articulate the research question. The primary source of literature was Scopus, chosen for its extensive coverage of research in the domains of bio-circular economy and waste valorisation.

The review integrated peer-reviewed literature in conjunction with a solitary grey-literature source, namely the Circularity Gap Report (2025), to ascertain circular performance indicators and system-level design benchmarks. This inclusion was justified by the report's methodological rigor and international relevance. This report provided internationally recognised key performance indicators (KPIs), including waste-diversion rate, secondary-material substitution rate, and overall system circularity, which serve as guiding metrics in later validation stages of the model.

4.1 Step 1: Review objective and research questions

The intent of this scoping review was to systematically synthesise the current practices within the circular economy, as well as the associated system components and system prerequisites, which have been either implemented or proposed for the management of organic waste within agri-food systems. The primary research question was articulated as follows:

- *What circular economy strategies, system components, and system requirements have been proposed or implemented to manage organic waste in agricultural and tourism-linked systems, particularly in conservation or remote contexts?*

This was supported by the following research questions (RQ):

- RQ1 - What are the dominant CE strategies used in food, agricultural, and conservation systems?
- RQ2 - What technical or systemic components are involved in waste valorisation?

- RQ3 - What are the standard material inputs, processing methods, outputs, and feedback mechanisms?
- RQ4 - What enabling conditions or constraints are relevant for CE implementation in these contexts?

The scoping review intentionally included both empirical and conceptual studies to support the identification of functional system elements as well as behavioural and institutional system enablers.

4.2 Step 2: Search strategy and study selection

The Scopus database was utilised for the literature review due to its extensive coverage across diverse disciplines, encompassing environmental sciences, agriculture, engineering, and sustainability. The search methodology was structured in accordance with the PCC (Population-Concept-Context) framework, which is advocated for scoping reviews to ensure congruence between the research inquiry, inclusion criteria, and search terminologies (Peters et al., 2015). The application of the framework was as follows:

- **Population:** Organic waste streams relevant to agri-food systems, including food waste, agricultural waste, biowaste, manure, and post-consumer organics.
- **Concept:** Circular economy strategies, including resource recovery, waste valorisation, closed-loop systems, nutrient cycling, and material reuse.
- **Context:** Decentralised, conservation-oriented, or resource-constrained environment, such as farms, protected areas, nature reserves, and ecotourism systems, particularly within arid or semi-arid regions.

This framework guided both the construction of the Boolean search string and the definition of inclusion/exclusion criteria, as seen in Table 1.

Table 1 Search protocol for the scoping review

Element	Description
Research Question	Which circular economy practices, system components, and system requirements have been proposed or implemented to manage organic waste in agricultural and tourism-linked systems, particularly in conservation or remote contexts?
Secondary questions	What are the dominant CE strategies used in food, agricultural, and conservation systems?
	What technical or systemic components are involved in waste valorisation?
	What are the common material inputs, processing methods, outputs, and feedback mechanisms?

	What enabling conditions or constraints are relevant for CE implementation in these contexts?
Field	Environmental Science, Agricultural & Biological Sciences, Engineering
Database	Scopus
Date searched	29/07/2025
Search string	("circular economy" OR "closed-loop system*" OR "resource recovery" OR "waste valorisation") AND ("organic waste" OR "agricultural waste" OR "food waste") AND ("agriculture" OR "circular agriculture" OR "food system*" OR "ecotourism" OR "protected area*" OR "nature reserve*" OR "conservation area*") AND ("design requirement*" OR "system design" OR "model*" OR "framework*" OR "waste management") AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "AGRI") OR LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (EXACTKEYWORD , "Circular Economy") OR LIMIT-TO (EXACTKEYWORD , "Waste Management") OR LIMIT-TO (EXACTKEYWORD , "Agriculture") OR LIMIT-TO (EXACTKEYWORD , "Food Waste")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Israel") OR LIMIT-TO (AFFILCOUNTRY , "Botswana") OR LIMIT-TO (AFFILCOUNTRY , "Namibia") OR LIMIT-TO (AFFILCOUNTRY , "Mozambique") OR LIMIT-TO (AFFILCOUNTRY , "Qatar") OR LIMIT-TO (AFFILCOUNTRY , "Saudi Arabia") OR LIMIT-TO (AFFILCOUNTRY , "Zimbabwe"))
Inclusion criteria	Studies on circular-economy practices, waste-valorisation, or system design in agriculture, food systems, or conservation must address sustainable resource use, closed-loop or regenerative processes, or CE-related technologies for organic waste management.
Exclusion criteria	Publications without circular economy, waste management, or sustainability discussion; studies on linear or purely theoretical models irrelevant to material/resource flows; and research not related to agricultural, ecological, or conservation systems.
Years	2015-2025
Language	English only
Geography	Global (but flag Africa/South Africa for relevance)
Publication Type	Peer-reviewed journal articles, conference papers, review articles
Topic	CE models, organic waste, agri-food systems, protected areas, ecotourism

Search terms included:

- Population: "organic waste", "food waste", "agricultural waste", "biowaste"
- Concept: "circular economy", "resource recovery", "closed-loop systems", "waste valorisation"
- Context: "agriculture", "food systems", "ecotourism", "protected area", "nature reserve", "conservation area".

A Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) flow diagram summarising the screening process is provided in Figure 1. A total of 299 records were retrieved and screened in two stages. First, titles and abstracts were screened for thematic relevance. If the title or abstract did not mention circular economy or any related term e.g. bioeconomy, circular agriculture, valorisation or circular supply chains, it was excluded. Second, full-text reviews were conducted to assess inclusion based on the following criteria:

- Describes or proposes CE strategies applicable to organic/agricultural waste.
- Contains design-relevant information e.g. system structure, flows, feedback.
- It is contextually aligned with decentralised, low-resource, or conservation-oriented systems.
- Includes conceptual or policy-based insights relevant to CE implementation.

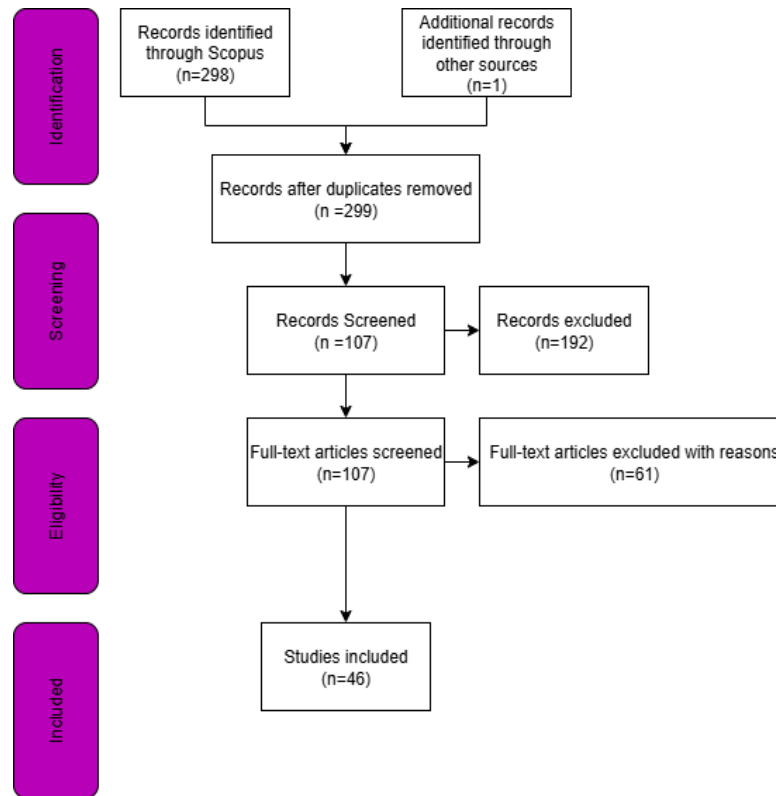


Figure 1 Scoping review based on PRISMA guidelines

The country set was bounded to the focal geography (South Africa) and its neighbours with comparable semi-arid ecologies and conservation-led land uses (Botswana, Namibia, Mozambique, Zimbabwe), and arid to hyper-arid reference states with mature practice in water reuse and resource-recovery relevant to on-site CE systems (Israel, Qatar, Saudi Arabia). This mix was selected to maximise contextual transferability: similar climate stressors (semi-arid/arid), protected-area/ecotourism operations, and infrastructure constraints, while also sampling higher-technology envelopes for contrast. A total of 45 peer-reviewed articles sourced from the Scopus database were selected for inclusion in the data synthesis process. The Circularity Gap Report (2025) was incorporated as supplementary grey literature, serving to contextualise the global circular-economy indicators and furnishing baseline metrics.

During title and abstract screening, 192 records were excluded on grounds as follows:

- **Topic out of scope** (e.g. plastics, general MSW without an organic valorisation focus, unrelated technologies).
- **Wrong system/context** (no agri-food, conservation, ecotourism or campus/service settings).

Following full-text retrieval, 61 articles were excluded for the reasons below:

- **Insufficient extractable design/operational detail** (conceptual or review pieces without methods/KPIs needed for coding).
- **No organic-waste valorisation intervention** (non-organic focus on closer reading).
- **Context not transferable** (purely municipal/high-income urban systems with no relevance to remote/conservation settings).
- **Outcomes not aligned to the model scope** (products/uses not applicable to on-site loop closure).

A structured data extraction table was developed to capture both descriptive and design-relevant attributes of each included study. The extracted data were thematically coded and grouped according to functional system categories. A total of 45 peer-reviewed articles were retained following the screening process. These studies span diverse contexts, including agricultural waste valorisation, food-system circularity, bioenergy production, and conservation-linked sustainability practices. A complete list of all included studies is provided in Appendix A (Table A1).

5 Findings

This scoping review synthesises evidence from 46 studies to elaborate on circular economy practices, system components, and system requirements pertinent to the valorisation of organic waste within systems related to agriculture and tourism. The synthesis adhered to the guidelines proposed by Levac et al. (2010), integrating descriptive numerical summaries with qualitative thematic analysis to discern recurring patterns across studies. Additionally, a narrative synthesis approach was employed to amalgamate findings from diverse methodological frameworks and geographic contexts. The review encompasses evidence from a spectrum of climatic regions and sectoral contexts, with significant representation from sub-Saharan Africa, North Africa, the Middle East, and South Asia, regions where resource constraints and innovation in the circular bioeconomy are particularly pronounced.

5.1.1 Coding scheme for design evidence

Extracted information from the literature were tagged with concise evidence codes indicating both type and origin. Differentiation was made for systems requirements (hard conditions), enablers

(contextual factors that improve adoption/performance), constraints (boundary conditions that limit options), and recommendations (desirable “nice-to-have” features).

Codes adopt the form (Type-Source-Index), where Type $\in$ (DR systems requirement, EN enabler, CN constraint, RC recommendation); Source $\in$ (LIT literature, LEG legislation/policy, EMP empirical/site); Index is a running number. The 1xx block is reserved for RQ1 items such that later sections can add 2xx/3xx blocks without conflict. *E.g. maintain C:N 25-35, moisture 50-60%, aeration, and achieve maturity before land application (DR-LIT-101)*

5.1.2 Circular economy practices for organic waste management

Circular management of organic waste uses biological and thermochemical processes to convert residues like food waste and biosolids into nutrient-rich or energy-rich products. These technologies share the goal of preserving material value, regenerating nutrients, and reducing emissions from decomposition. Six main processes, shown in Figure 2, form the foundation of circular bioresource systems in agriculture, waste management, and conservation.

Collectively, these pathways constitute an integrated ensemble of technologies designed to facilitate decentralised circular systems. Composting and anaerobic digestion play pivotal roles in stabilising biodegradable substrates while facilitating the return of essential nutrients to the soil. Black soldier fly larvae (BSFL) processing transforms high-moisture food residues into valuable protein and frass. Thermochemical processes, including the production of biochar and the application of hydrothermal carbonisation (HTC), serve to enhance carbon retention and improve soil structure. Additionally, nutrient recovery from wastewater, shown by struvite precipitation, is instrumental in closing mineral loops that are crucial for water-efficient horticulture. The studies under review

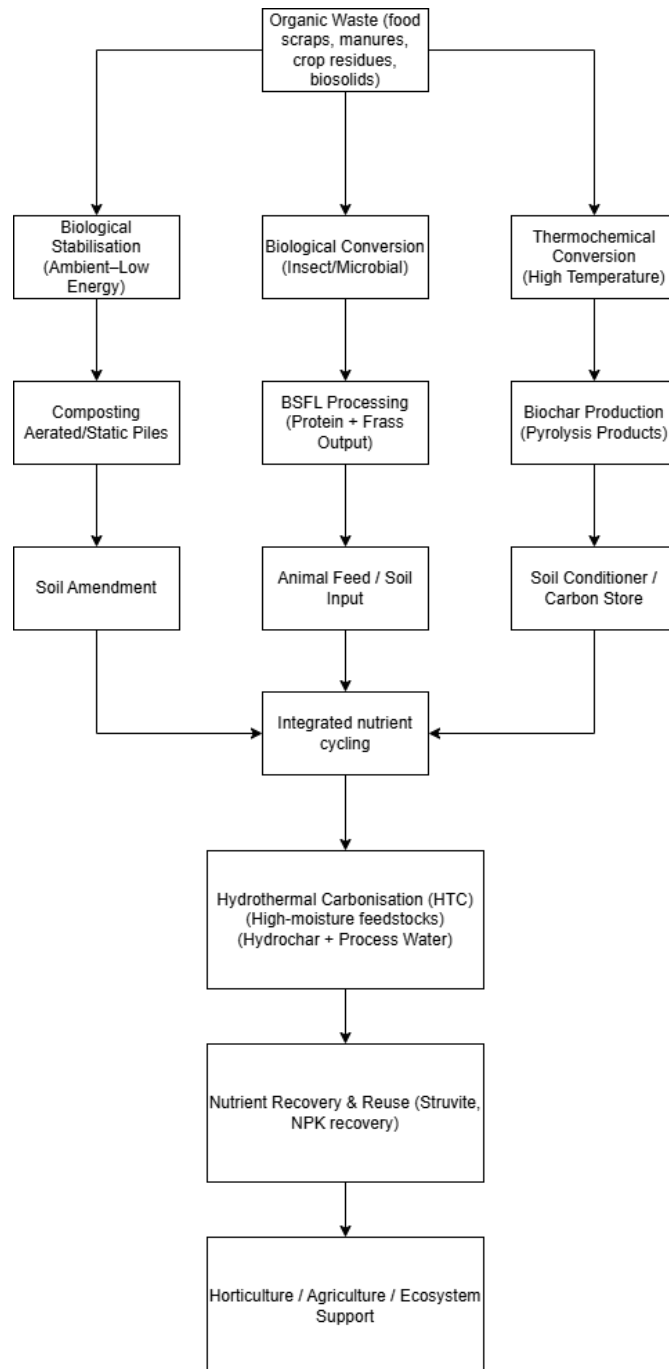


Figure 2 Primary methods for organic waste valorisation in circular systems

demonstrate that these processes are frequently integrated to optimise labour demand, energy availability, and output quality, particularly within remote or resource-limited environments.

This subsection identifies dominant practices and records strategy-level requirements/recommendations (DR/RC-LIT-1xx). Across the reviewed literature, a wide range of CE practices were documented, each contributing to the reduction, recovery, or valorisation of organic waste:

- Composting (Ofei-Quartey et al., 2023)

- Anaerobic digestion (Areeshi, 2022)
- Black soldier fly larvae (BSFL) conversion (Mlambo et al., 2023)
- Biochar production (Pradhan et al., 2024)
- Hydrothermal carbonisation (Diab et al., 2025)
- Nutrient recovery processes such as struvite precipitation (Chandrasekaran et al., 2024)

At a strategic level, the minimum systems requirements statements are normalised as follows:

- (DR-LIT-101) - composting shall meet basic process-control and maturity requirements.
- (DR-LIT-102) - anaerobic digestion shall specify HRT/SRT and temperature regime and manage digestate for reuse
- (DR-LIT-103) - BSFL systems shall ensure hygiene, odour/vector control and safe frass use.
- (DR-LIT-104; DR-LIT-105) - biochar and HTC shall document operating windows and characterise products before agronomic application.
- (DR-LIT-106) - struvite systems shall control dosing/pH and meet fertigation product specs.
- Where labour or utilities are limiting, aerated static piles for composting (RC-LIT-101) and on-site heat use for AD are recommended (RC-LIT-102)

These practices were applied across agriculture, waste management, food systems, protected area governance, and urban sustainability. In many cases, multiple processes were integrated to maximise resource recovery and system resilience, for example co-managing food waste and livestock manure to optimise nutrient recovery (Xu et al., 2024). Applications ranged from small-scale pig farming (Mathobela et al., 2024) and urban composting (Ofei-Quartey et al., 2023) to biosolid reuse in agriculture (Carter et al., 2025). Many interventions were explicitly linked to broader objectives such as food security, waste minimisation, nutrient cycling, and water conservation.

5.1.3 System components and material flows

This subsection specifies system stages, control parameters and quality assurance (QA), and the supply-chain/monitoring layer (DR/RC-LIT-2xx). The reviewed systems consistently incorporated three interlinked functional elements:

- **Input streams:** Organic waste from kitchens and hospitality operations, agricultural residues, market biowaste, greywater, biosolids, and livestock manure (Okuthe, 2024, Carter et al., 2025). Source separation and contamination control at collection are required (DR-LIT-201). In several cases, co-processing of multiple waste types improved efficiency and resource recovery (Xu et al., 2024) (RC-LIT-201).

- **Processing nodes:** Decentralised composting hubs, anaerobic digestion units, BSFL bioconversion facilities, hydrothermal carbonisation reactors, and nutrient recovery systems (Lorick et al., 2020, Garg et al., 2024). Nodes should be configured to fit local utilities, skills and loads (DR-LIT-203), with documented operating controls and basic QA (RC-LIT-202).
- **Output loops:** Organic fertilisers (compost, frass), biogas, larvae protein, treated greywater, and other recovered resources. Outputs shall be reintegrated into proximate sinks (soils, feed, heat, irrigation) with defined quality thresholds and records (Sobaih and Elnasr, 2023, Mathobela et al., 2024) (DR-LIT-204).

Feedback mechanisms, such as the reintegration of compost into agricultural systems or the redirection of greywater to aquaponic setups, play a crucial role in maintaining the circularity of these systems Sobaih and Elnasr, 2023; Mathobela et al., 2024) (RC-LIT-205).

5.1.4 Enabling conditions and constraints

This subsection collates cross-cutting enablers and constraints and any universal systems requirements: (EN/CN-LIT-3xx; DR-LIT-3xx)

Enabling conditions:

- **Behavioural readiness and awareness:** Community and consumer engagement significantly influenced waste separation, contamination rates, and the quality of recovered materials (Sobaih and Elnasr, 2024; Patel et al., 2021) (EN-LIT-301).
- **Policy and institutional support:** Municipal involvement, regulatory clarity, and targeted policy incentives supported adoption and scaling (Dzawanda et al., 2025) (EN-LIT-302).
- **Technology appropriateness:** Affordability, scalability, and ease of maintenance were essential to ensure long-term viability, particularly in low-resource settings (Siddiqui et al., 2025, Okuthe, 2024) (EN-LIT-303).
- **Risk governance:** The implementation of contaminant monitoring, hygiene education, and adherence to safety regulations ensures that the reutilisation of biosolids and greywater is maintained as both safe and societally acceptable (Carter et al., 2025) (EN-LIT-304).

Constraints:

- **Seasonal variability** in waste generation, affecting load, buffer sizing, and utilisation (CN-LIT-302).
 - Food-service and campus operations exhibit marked intra-year variability in waste volumes and composition, which complicates capacity planning and undermines steady-state utilisation without buffers (Leal Filho et al., 2024).

- Regional and socio-economic shocks (e.g., COVID-19) and cultural calendars alter household and supply-chain food waste volumes in arid areas, underscoring the necessity for adaptable sizing and operational policies (Baya Chatti et al., 2024).
- In sub-Saharan African fresh-produce chains, perishability and seasonal gluts cause fruit and vegetable waste to vary at farms, markets, and processors. This means that collection and valorisation logistics need to be flexible (Okuthe, 2024).
- UK evidence on avoidable food waste shows that seasonality, behaviour, and menu cycles are the main causes of variability. This affects storage and redistribution capacities (Patel et al., 2021).
- **Limited technical capacity** in remote operations, affecting technology selection and necessitating operator training (CN-LIT-303).
 - Reviews of the adoption of a circular economy consistently point to skills and organisational capabilities as major barriers to implementation and growth, especially in places that aren't well-resourced (Pasqualotto et al., 2023, Hina et al., 2023).
 - Mapping of "green technology" trends in waste management identifies capability deficiencies and the necessity for training to utilise even moderately complex digital and sorting systems (Tanveer et al., 2022).
 - Agricultural ecotechnologies exhibit performance that is significantly influenced by context; their successful implementation in low-capacity environments relies on suitability and operator expertise (Lorick et al., 2020).
- **High initial investment** requirements and limited access to capital, impacting viable technology configurations and timelines (CN-LIT-304).
 - Financial barriers, payback uncertainty and access to capital recur as primary impediments to circular business models and reverse-logistics systems, shaping which technologies are feasible and when (Hina et al., 2023; Pasqualotto et al., 2023).
 - Infrastructure optimisation studies for biomass reuse show that transport and energy economics dominate feasibility, implying staged roll-out and blended finance for capital-intensive options (Shwartz and Oron, 2025).
 - National-level food-sector analyses in arid economies emphasise that policy incentives and public investment are frequently prerequisites for the private implementation of CE technologies (Almulhim, 2024).
- **Infrastructure gaps** (power, water, transport, laboratories) that make it hard to control processes, manage logistics, and gather evidence of compliance (CN-LIT-305).
 - Field studies in semi-arid African cities say that weak collection systems and limited recycling infrastructure are the main problems, and that unreliable transport and power affect operations (Jerie et al., 2024).

- Entrepreneurship-oriented reviews for SSA identify cold-chain logistics, road infrastructure, and basic utilities as critical impediments to the valorisation of perishable residues (Okuthe, 2024).
- In dry countries, a lack of water and broken infrastructure limit CE options and require system design that is guided by policy (Almulhim, 2024).
- Biosolids/circular-water literature emphasises the need for robust monitoring and laboratory capacity (e.g. for PFAS, ARGs, metals) to demonstrate compliance and manage risk, often lacking in remote/low-resource settings (Xue et al., 2025).
- Institutional waste-reduction programmes stress that reliable measurement systems and basic QA/monitoring infrastructure are prerequisites for continuous improvement and regulatory reporting (Leal Filho et al., 2024).

Minimum monitoring shall be in place before land or food-chain application of recovered products e.g. compost maturity, digestate/struvite nutrient-metal checks and water-quality parameters (DR-LIT-301).

5.1.5 Circularity performance indicators

The Circularity Gap Report (2025) offers a standardised array of indicators for assessing circularity in systems. These metrics serve as a reliable and transferable standard for assessing the technical, environmental, and operational efficacy of CE interventions. Table 2 describes each KPI.

Table 2 CGR (2025) Key Performance Indicators

Indicator	Description
Waste-diversion rate (%)	Share of waste rerouted from landfills to valorisation processes
Waste-conversion rate (%)	Proportion of input waste transformed into usable outputs
Resource-efficiency ratio (kg/kg)	Output produced per unit input consumed
Secondary-material substitution (%)	Degree to which virgin inputs are replaced by recovered materials
Reserve-level circularity (%)	Total percentage of material flows recirculated within the closed system
System Performance Index (0-100)	Composite score combining environmental, economic, and operational metrics

5.2 Register and summary of coded design evidence

This section consolidates the normalised evidence from the previous sections into a transparent register that can be carried forward into the design phase of future CE design and implementation endeavours. Each item is coded as a systems requirement (DR-LIT-xxx), recommendation (RC-LIT-xxx), enabler (EN-LIT-xxx), or constraint (CN-LIT-xxx), with number blocks aligned to subsection scope (1xx = practices; 2xx = system components; 3xx = enablers/constraints). For every code, the register records an abridged statement, key evidence anchors which are the sources and the affected process nodes. A summary in Table 3 reports tallies by code type.

Table 3 Register for LIT codes

ID	Type	Normalised statement	Evidence anchors (sources)	Applies to
DR-LIT-101	DR	Composting shall meet basic process control (C:N, moisture, aeration) and achieve maturity before land application.	Ofei-Quartey et al., 2023	Composting node
RC-LIT-101	RC	Where labour is scarce, prefer aerated static piles for composting.	Ofei-Quartey et al., 2023	Composting layout
DR-LIT-102	DR	Anaerobic digestion shall specify HRT/SRT and temperature regime; digestate shall meet reuse quality.	Areeshi, 2022; Abbas et al., 2023	AD module
RC-LIT-102	RC	Prioritise on-site biogas for heat to shorten loops.	Abbas et al., 2023; Garg et al., 2024	Energy integration
DR-LIT-103	DR	BSFL systems shall ensure hygiene, odour/vector control, and safe frass handling for soil use.	Mlambo et al., 2023	BSFL unit
DR-LIT-104	DR	Biochar systems shall document operating window and characterise product (BET/CEC, contaminants) before agronomic use.	Pradhan et al., 2024	Biochar line
RC-LIT-104	RC	Consider dual use of biochar as soil conditioner and filtration medium.	Pradhan et al., 2024; Garg et al., 2024	Soil/water loops

ID	Type	Normalised statement	Evidence anchors (sources)	Applies to
DR-LIT-105	DR	HTC shall control process conditions, manage process water, and characterise hydrochar prior to use.	Diab et al., 2025	HTC line
RC-LIT-105	RC	Deploy HTC only where utilities and water management are adequate.	Diab et al., 2025	Siting/feasibility
DR-LIT-106	DR	Struvite recovery shall control Mg:P dosing and pH; product shall meet fertigation specification.	Chandrasekaran et al., 2024	Nutrient recovery
RC-LIT-106	RC	Integrate struvite into on-site fertigation to substitute virgin inputs.	Chandrasekaran et al., 2024	Loop-closure
RC-LIT-107	RC	Co-manage food waste with manures where feasible to optimise recovery.	Xu et al., 2024	Feed strategy
DR-LIT-201	DR	Source separation and contamination control at collection are required.	Ofei-Quartey et al., 2023; Leal Filho et al., 2024	Collection/pre-processing
RC-LIT-201	RC	Use co-processing of multiple waste types to improve recovery where beneficial.	Xu et al., 2024	Feed blending
RC-LIT-202	RC	Configure nodes to local utilities, skills, and loads; prefer modularity.	Lorick et al. (2020); Hina et al., 2023	Network design
DR-LIT-203	DR	Each processing node shall have documented operating controls and basic QA.	Ofei-Quartey et al., 2023; Chandrasekaran et al., 2024	All process units
DR-LIT-204	DR	Outputs shall be routed to proximate sinks (soils, feed, heat, irrigation) with defined quality thresholds and records.	Garg et al., 2024; van Rooyen et al., 2025	Loop-closure
RC-LIT-205	RC	Intentionally design feedback loops (co-location, short transfers, buffers).	Sobaih & Abu Elnasr, 2023; Mathobela et al., 2024	Layout/ops
EN-LIT-301	EN	Engagement and awareness enable high-quality source separation and low contamination.	Sobaih & Abu Elnasr, 2024; Patel et al., 2021	Behavioural programme

ID	Type	Normalised statement	Evidence anchors (sources)	Applies to
EN-LIT-302	EN	Municipal/institutional support and clear rules enable adoption and scaling.	Dzawanda et al., 2025; Leal Filho et al., 2024	Governance
EN-LIT-303	EN	Technology appropriateness (affordable, maintainable, modular) enables sustained operation.	Siddiqui et al., 2025; Okuthe, 2024	Technology choice
EN-LIT-304	EN	Risk-governance capacity (monitoring, training) enables safe reuse of biosolids/greywater.	Carter et al., 2025; Xue et al., 2025	QA & training
CN-LIT-302	CN	Seasonal variability drives load swings; requires buffers and flexible sizing.	Leal Filho et al., 2024; Okuthe, 2024; Baya Chatti et al., 2024; Patel et al., 2021	All nodes
CN-LIT-303	CN	Limited technical capacity narrows feasible technology sets and increases training needs.	Pasqualotto et al., 2023; Hina et al., 2023; Tanveer et al., 2022; Lorick et al., 2020	All nodes
CN-LIT-304	CN	High upfront costs and finance constraints necessitate phased roll-out.	Hina et al., 2023; Pasqualotto et al., 2023; Shwartz & Oron, 2025; Almulhim, 2024	Phasing/portfolio
CN-LIT-305	CN	Infrastructure gaps (power, water, transport, labs) constrain control, logistics, and compliance evidence.	Jerie et al., 2024; Okuthe, 2024; Almulhim, 2024; Xue et al., 2025; Leal Filho et al., 2024	Site readiness
DR-LIT-301	DR	Minimum QA/monitoring shall be in place before land/food-chain use of recovered products.	Carter et al., 2025; Ofey-Quartey et al., 2023	Cross-cutting
DR-LIT-401	DR	Compost control KPIs: temperature profile ($\geq$ threshold days) and GI maturity shall be evidenced.	Ofey-Quartey et al., 2023	Composting KPI set
DR-LIT-402	DR	AD KPIs: HRT/SRT within spec; specific biogas yield shall be reported.	Abbas et al., 2023	AD KPI set
DR-LIT-403	DR	BSFL KPIs: larvae conversion rate and frass quality shall meet defined thresholds.	Mlambo et al., 2023	BSFL KPI set

ID	Type	Normalised statement	Evidence anchors (sources)	Applies to
DR-LIT-404	DR	Struvite KPIs: P-content, impurities and recovery % shall meet fertigation specification.	Chandrasekaran et al., 2024	Struvite KPI set
DR-LIT-405	DR	Circularity KPIs: diversion %, N/P retention %, substitution ratios shall be tracked (aligned to CGR 2025).	CGR, 2025; Garg et al., 2024	System-level KPIs
RC-LIT-401	RC	Track water/energy intensity ($L \cdot kg^{-1}$; energy self-supply %) where contextually useful.	Diab et al., 2025; Garg et al., 2024	Resource KPIs

The register shows that systems requirements (DR-LIT) cluster around three pillars:

1. Front-end controls, source separation and contamination management (e.g. DR-LIT-201).
2. Process and product assurance. documented operating windows and release criteria before any land/food-chain application (e.g. DR-LIT-101; DR-LIT-301).
3. Loop closure with defined specifications, routing outputs to proximate sinks under explicit quality thresholds (DR-LIT-204).

Recommendations (RC-LIT) are concentrated in layout and operational choices (co-location, modularity, staged roll-out), which improve feasibility under the enablers (EN-LIT) identified (engagement, governance capacity, technology appropriateness). The constraints (CN-LIT), notably seasonality, capability, finance, and infrastructure, define the scenario bounds and justify a phased, modular design.

6 Discussion

The summary presented in Table 4 highlights the diversity and adaptability of circular economy strategies relevant to organic waste management and agri-food system design. The selected studies illustrate how waste-to-value interventions, when strategically structured, can simultaneously address environmental degradation, resource inefficiency, and food system resilience.

Table 4 Summary of CE strategies and their applications

Strategy	Input Type	Technology / Process	Output Product	Reuse Application
Bokashi composting	Food/kitchen waste	Anaerobic fermentation	Organic fertiliser	Vegetable beds, pig feed
Anaerobic digestion	Manure + food waste	Biogas reactor	Biogas + digestate	Energy + fertiliser
BSFL bioconversion	Food/market waste	Insect-based digestion	Protein + frass	Animal feed + compost booster
Biochar pyrolysis	Crop/FV residues	Low-temp pyrolysis	Charcoal soil additive	Water purification, soil remediation
Struvite precipitation	Sludge/greywater	Magnesium-based recovery	P-rich fertiliser	Nutrient cycling in fertigation
Hydrothermal carbonisation	Legume residues	High-pressure hydrothermal treatment	Soil enhancer + clean water	Hydroponics and irrigation

Across the corpus, organic residues are valorised through a modular portfolio of biological and physio-chemical routes, most commonly composting (Ofei-Quartey et al., 2023), anaerobic digestion (used as co-digestion) (Abbas et al., 2023), insect bioconversion via black soldier fly larvae (BSFL) (Mlambo et al., 2023), targeted nutrient recovery (Chandrasekaran et al., 2024), and carbon-rich amendments via pyrolysis or hydrothermal carbonisation (HTC) (Diab et al., 2025). These unit operations are deliberately co-located with on-site sinks (kitchen/process heat; horticulture; livestock; fertigation) to shorten loops, reduce haulage and decrease landfill dependence (Garg et al., 2024, van Rooyen et al., 2025). Tourism-linked sites and campuses contribute relatively clean, segregable organics when paired with source-separation and behaviour programmes, which improves diversion and stabilises feedstock quality (Leal Filho et al., 2024, Sobaih and Elnasr, 2024). When aqueous or solid side-streams are reused, such as reclaimed water or biosolids, risk governance necessitates contaminant monitoring and product standards before application to land or the food chain (Carter et al., 2025; Xue et al., 2025).

RQ1: Dominant circular-economy strategies in food, agricultural, and conservation systems

The dominant strategies are biological stabilisation and nutrient cycling (co-/composting; anaerobic digestion with land application of digestate), bioconversion to feed (BSFL), selective nutrient recovery (struvite), and carbon-centric amendments (food-waste biochar; HTC) that also deliver soil and water services (Ofei-Quartey et al., 2023, Abbas et al., 2023, Diab et al., 2025).

Managerial “R-hierarchy” measures in hospitality and education (menu/portion redesign, redistribution, source separation) are used to raise diversion baselines and feed steadier inputs to treatment nodes (Sobaih and Elnasr, 2024, Leal Filho et al., 2024). In low-infrastructure or remote contexts, decentralised, lower-complexity options (co-composting, BSFL, small-scale digestion, biochar) are prioritised, with higher-spec recovery e.g. struvite, added where utilities, skills and capital allow (Lorick et al., 2020; Garg et al., 2024).

RQ2: Technical or systemic components involved in waste valorisation

Technically, these systems follow a clear sequence. Upstream segregation and collection with contamination control is the first step, as shown in co-composting studies by Ofei-Quartey et al. (2023). Pre-processing then tunes feed characteristics, shredding and blending to set carbon-to-nitrogen (C:N) ratio and moisture (Ofei-Quartey et al., 2023). Conversion follows in reactors: composting in windrows or aerated static piles with ratio modelling (Ofei-Quartey et al., 2023); anaerobic co-digestion in continuous stirred-tank or plug-flow reactors (Abbas et al., 2023); black soldier fly larvae (BSFL) rearing for feed conversion (Mlambo et al., 2023); magnesium-assisted phosphorus precipitation to produce struvite (Chandrasekaran et al., 2024); and thermal routes such as pyrolysis and hydrothermal carbonisation for carbon-rich amendments (Pradhan et al., 2024, Diab et al., 2025). Product finishing and quality assurance close the loop: compost maturity/respiration and germination index (GI) (Ofei-Quartey et al., 2023); nutrient/metal limits for digestate and struvite (Chandrasekaran et al., 2024); proximate analysis for larvae meal (Mlambo et al., 2023); and biochar characterisation via Brunauer-Emmett-Teller (BET) surface area and cation-exchange capacity (CEC) (Pradhan et al., 2024).

Systemically, stable operation depends on coordinated reverse logistics and reliable market outlets, which Mahmoud et al. (2024) frame within circular supply-chain design. Stakeholder engagement and governance arrangements are equally pivotal for adoption and day-to-day discipline, as Hina et al. (2023) argue in the context of circular business models. Finally, digital and operational monitoring, from simple mass-balance checks to IoT-enabled forecasting, helps smooth variability and sustain performance over time (Tanveer et al., 2022).

RQ3: Common inputs, processing methods, outputs, and feedback mechanisms

In continuation of the node inventory, the predominant inputs are identified as kitchen and plate waste, produce residues, manures, pruning fractions, and nutrient-rich side streams (Okuthe, 2024; Ofei-Quartey et al., 2023). The processing methodologies employed include co-composting with optimised ratios, co-digestion of manures and food waste, bioconversion via BSFL, pyrolysis of food waste to biochar, hydrothermal carbonisation (HTC) of moist residues, and struvite

precipitation from liquors enriched in ammonium and phosphate (Abbas et al., 2023; Pradhan et al., 2024; Diab et al., 2025).

The resultant outputs include compost and digestate, biogas and thermal energy, protein meal and frass, biochar, struvite granules, and treated water. Feedback mechanisms are deliberately designed to substitute for virgin inputs; compost, digestate, biochar, and struvite are reincorporated as amendments for soil and irrigation purposes. Concurrently, larvae meal serves as an alternative to commercial feed, and biogas is employed in renewable energy applications (Garg et al., 2024; van Rooyen et al., 2025).

Figure 3 provides a functional block diagram derived from a synthesis of the reviewed literature to illustrate these interactions. The diagram shows the interrelationships between the main valorisation pathways and their associated material and energy fluxes. Each subsystem, encompassing anaerobic digestion, livestock feeding, microbial fermentation, and nutrient recovery, functions dually as a consumer and supplier within the integrated network.

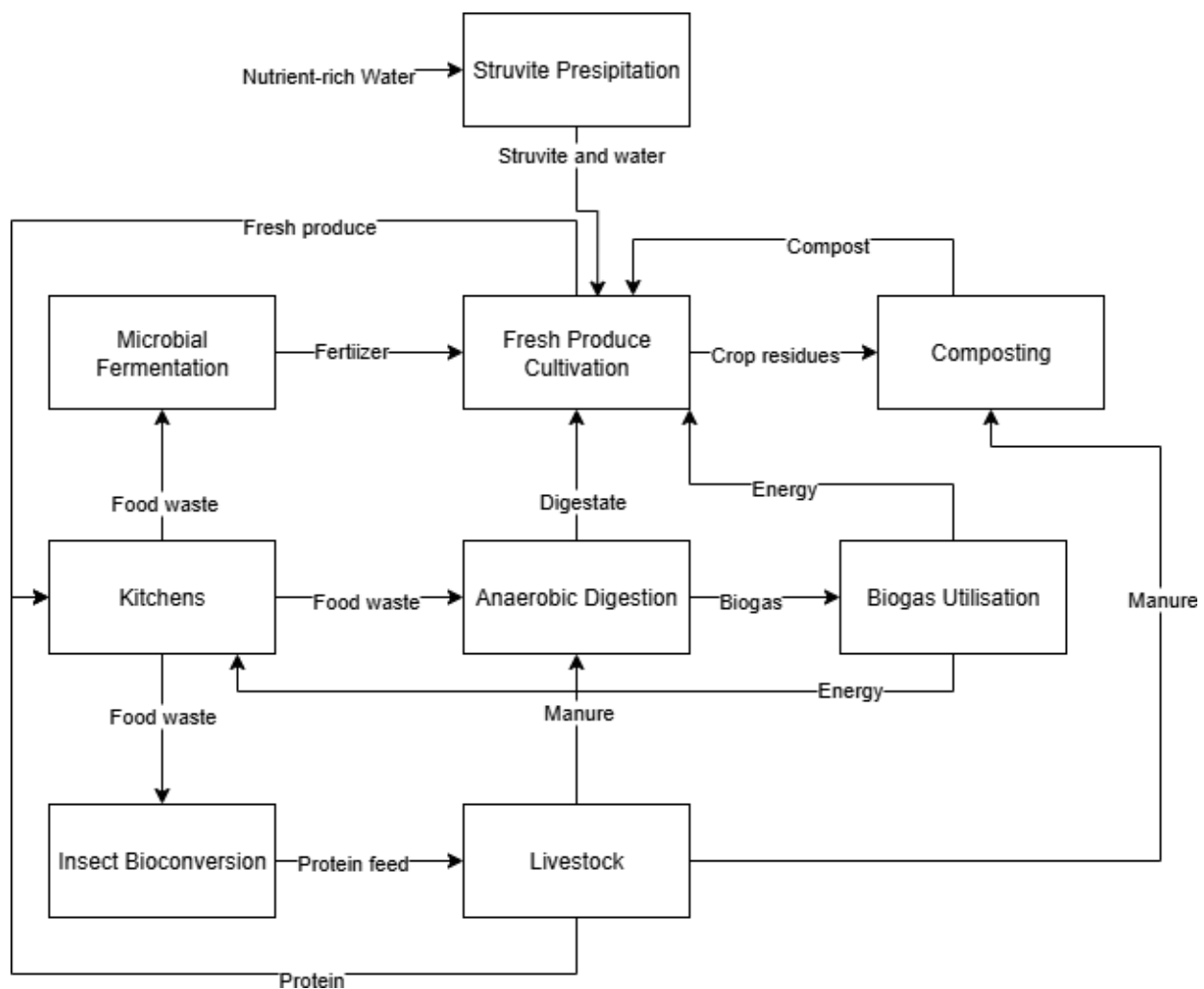


Figure 3 Functional block diagram of integrated organic-waste valorisation processes

The block diagram representation depicts the role of kitchen organic waste as a communal feedstock for multiple processing pathways, thereby fostering material reutilisation as opposed to linear disposal. The cycling of manure and digestate occurs among livestock management, anaerobic digestion, and composting procedures. The recovery of nutrients, demonstrated by struvite precipitation, facilitates the conversion of wastewater into fertilizers suitable for the cultivation of fresh produce. The energy derived from biogas serves to offset the energy demands of these processes, while microbial fermentation contributes by generating value-added fertilizers.

This closed-loop framework embodies a circular resource symbiosis, which enhances system resilience through the integration of biological, energy, and nutrient cycles. By processing waste on-site via multiple pathways, the system diminishes dependency on external resources, bolsters local food production, and aligns with the objectives of a circular bioeconomy, especially in remote or conservation-focused areas.

RQ4: Enabling conditions and constraints for implementation in these contexts

Enablers include sustained participation and source separation in service environments: on campuses, Leal Filho et al. (2024) demonstrate that measurement-plus-engagement programmes lift diversion and stabilise feed quality; in family restaurants, Sobaih and Abu Elnasr (2024) show that 5Rs practices and managerial nudges reduce plate waste; and in an urban open market, Dzawanda et al. (2025) find that education and policy engagement predict uptake. Institutional backing and incentives, coupled with business-model alignment, are also decisive for adoption and day-to-day discipline, as argued by Hina et al. (2023).

Constraints recur across the corpus. Seasonal variability in waste streams affects loading and sizing, Leal Filho et al. (2024) report intra-year swings in campus food waste, while Okuthe (2024) describes perishable gluts in SSA fruit-vegetable chains. Limited technical capacity in remote operations narrows feasible technology sets: Pasqualotto et al. (2023) synthesise skills and organisational capability gaps as core barriers, and Lorick et al. (2020) show that ecotechnology performance is highly context-dependent and operator-sensitive. High upfront costs and restricted finance encourage staged roll-out, Hina et al. (2023) identify capital constraints across circular business models; optimisation work on pruning-waste reuse indicates transport and energy economics necessitate phasing (Shwartz and Oron, 2025). Almulhim (2024) notes that policy incentives are often a precondition for private adoption. Infrastructure gaps, power, water, transport and laboratory capacity, constrain process control, logistics and compliance evidence. Jerie et al. (2024) document unreliable collection and limited facilities in semi-arid urban contexts;

Baya Chatti et al. (2024) highlight system fragilities during shocks; and Xue et al. (2025) stress that biosolids reuse demands monitoring and laboratory capability that many sites lack.

Taken together, the evidence supports phased, modular deployment: begin with “low-regret” nodes such as co-/composting and BSFL where utilities and skills are thin (Lorick et al., 2020, Mlambo et al., 2023), then layer higher-complexity recovery, AD up-scaling (Abbas et al., 2023), struvite precipitation (Chandrasekaran et al., 2024) and HTC (Diab et al., 2025), as capacity and capital mature. Supply-chain modelling reinforces the case for staged, coordinated roll-out (Mahmoud et al., 2024), and bioenergy syntheses support a diversified portfolio approach (Garg et al., 2024).

Finally, performance tracking is increasingly explicit, with process and circularity metrics reported across digestion, composting and recovery studies e.g. specific biogas yields, removal/recovery efficiencies, product quality indices. The indicators used here mirror those assembled in section 4.3.4 from the Circularity Gap Report (2025), ensuring consistency of later verification and validation (DSR 5) metrics. Ultimately, this synthesis specifies the feasible option set and design heuristics carried into the design phase.

7 Conclusions and recommendations

The empirical basis for a circular economy model has been systematically established through the sequential resolution of four research questions. The literature identifies a set of strategies, including co-composting, anaerobic digestion, bioconversion utilising black soldier fly larvae, selective nutrient recovery, and carbon-focused pathways. These strategies are commonly implemented in modular configurations and are often co-located with on-site sinks to minimise material loop length and reduce reliance on external resources. From a technical standpoint, these systems involve upstream separation and pre-processing, conversion within reactors selected according to specific criteria, and product finishing enhanced by quality assurance protocols. Methodologically, these systems depend on coordinated reverse logistics, stakeholder governance, and rigorous operational monitoring.

The review delineates essential system requirements for integrated organic-waste management systems, emphasising the need for decentralised processing that aligns with the spatial distribution of feedstocks. It advocates for the incorporation of multi-stream nodes capable of producing diverse outputs, alongside adaptive control mechanisms that accommodate seasonal variations. Furthermore, the implementation of transparent monitoring systems is critical to fostering user trust. Opportunities for valorisation within conservation and eco-tourism sectors are identified, focusing on the transformation of organic waste from hospitality services and small-scale agriculture into valuable products such as compost, biofertilizers, and protein feed. This

approach aims to enhance self-sufficiency, minimise waste transport, and advance environmental objectives within protected areas.

Despite promise, challenges like limited technical capacity, inconsistent waste segregation, and financing constraints remain. Success relies on social participation, source separation, institutional incentives, and aligning technology with context. Ongoing issues such as feedstock variability, energy costs, and infrastructure gaps require context-sensitive design and phased adoption.

Future research should establish modular nodes within the circular economy framework for conservation and ecotourism to empirically assess performance in varied environments. Later stages can include economic modelling, life-cycle assessments, and carbon-footprint analysis to measure environmental benefits. Integrating tools like Circular Value Stream Mapping, Lean diagnostics, process-efficiency audits, Material Flow Analysis, and quantitative modelling will better characterise system dynamics, resource flows, and bottlenecks. These methods create a structured path to convert circular-economy strategies into practical, contextual design solutions, addressing empirical and methodological gaps in circular waste valorisation research in protected and ecotourism areas.

Within the sphere of industrial engineering, further exploration is necessary regarding system optimisation, digital monitoring, and the expansion of integrated valorisation clusters within regional protected areas. These initiatives aim to transform the theoretical model into a validated decision-support system, facilitating transitions towards a circular bioeconomy in contexts characterised by limited data and resources.

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Appendix A

Table A1 List of included studies

#	Title	Authors
1	Green Catalysis: The Role of Medicinal Plants as Food Waste Decomposition Enhancers/Accelerators	Mugivhisa L.L.; Manganyi M.C.
2	Environmental impacts of plastic waste management practices in urban suburbs areas of Zimbabwe	Jerie S.; Chireshe A.; Shabani T.; Shabani T.; Maswoswere P.; Mudyazhezha O.C.; Mashiringwani C.; Mangwandi L.
3	Transesterification of neem seed oil for environmentally friendly biolubricants: Promoting circular economy in industrial processes	Rajak A.K.; Harikrishna M.; Zeenath S.F.; Dalal S.; Karuna M.S.L.; Rajesh K.; Pothu R.; Vennu V.; Boddula R.; Padmaja K.V.
4	Waste is the Best: An Approach to Circular Economy	Siddiqui M.W.; Akbar U.; Mondol M.S.A.; Abdi G.; Kasote D.M.; Dar A.H.
5	Struvite in circular economy: Production techniques, emerging applications and market opportunities	Chandrasekaran S.; Zaffar A.; Balasubramanian P.
6	Rethinking food loss and waste to promote sustainable resource use and climate change mitigation in agri-food systems: A review	Adelodun B.; Agbelusi O.O.; Soma T.; Odey G.; Adeyi Q.; Kumar P.; Ajibade F.O.; Goala M.; Silva L.F.O.; Mostafa Y.S.; Singh R.; Choi K.S.; Eid E.M.
7	Co-contaminant risks in water reuse and biosolids application for agriculture	Carter L.J.; Adams B.; Berman T.; Cohen N.; Cytryn E.; Elder F.C.T.; Garduño-Jiménez A.-L.; Greenwald D.; Kasprzyk-Hordern B.; Korach-Rechtman H.; Lahive E.; Martin I.; Ben Mordechay E.; Murray A.K.; Murray L.M.; Nightingale J.; Radian A.; Rubin A.E.; Sallach B.; Sela-Donenfeld D.; Skilbeck O.; Sleight H.; Stanton T.; Zucker I.; Chefetz B.
8	Enhancing Environmental Sustainability in the Mining Industry: Circular Economy Strategies for Resource Management and Digital Integration	Zhu W.; Kong D.; Ye Q.; Zhang X.; Tian D.; Solangi Y.A.
9	Lentil Hydrothermal Carbonization: A Dual Solution for Water Purification and Growth Enhancement	Diab T.; Hejazi A.; Hugerat M.; Asli S.; Diab M.

10	Prospects for Circular Economy Adoption in an Urban Open Market: Case Study of Mtapa Open Market, Gweru	Dzawanda B.; Maderera T.L.; Matsa M.M.
11	Valorizing Fruit and Vegetable Waste: The Untapped Potential for Entrepreneurship in Sub-Saharan Africa—A Systematic Review	Okuthe G.
12	Closing the Loop: Exploring Food Waste Management in the Near East and North Africa (NENA) Region during the COVID-19 Pandemic	Baya Chatti C.; Ben Hassen T.; El Bilali H.
13	Waste to wealth: microbial-based valorization of grape pomace for nutraceutical, cosmetic, and therapeutic applications to promote circular economy	Sodhi G.K.; Kaur G.; George N.; Walia H.K.; Sillu D.; Rath S.K.; Saxena S.; Rios-Solis L.; Dwibedi V.
14	Impact of Combined Application of Swine Manure Liquid and Phosphorus Fertilizers on Soil Phosphorus and Microbial Communities	Pu M.; Zhang Y.; Mukherjee S.; Alharbi S.F.; Singh R.K.; Abou-Elwafa S.F.; Trindade H.; Zhang T.
15	From Your Plate to Our Bin: Tackling Food Waste in Saudi Family Restaurants	Sobaih A.E.E.; Elnasr A.E.A.
16	Toward food waste reduction at universities	Leal Filho W.; Ribeiro P.C.C.; Setti A.F.F.; Azam F.M.S.; Abubakar I.R.; Castillo-Apráiz J.; Tamayo U.; Álzugar P.G.; Frizzo K.; Borsari B.
17	Biowaste to bioenergy nexus: Fostering sustainability and circular economy	Garg A.; Basu S.; Shetti N.P.; Bhattu M.; Alodhayb A.N.; Pandiaraj S.
18	Food waste biochar: a sustainable solution for agriculture application and soil—water remediation	Pradhan S.; Parthasarathy P.; Mackey H.R.; Al-Ansari T.; McKay G.
19	Circular economy: A review of review articles	Hossain M.; Park S.; Suchek N.; Pansera M.
20	Rethink biosolids: Risks and opportunities in the circular economy	Xue J.; Verstraete W.; Ni B.-J.; Giesy J.P.; Kaur G.; Jiang D.; McBean E.; Li Z.; Shin H.-M.; Xiao F.; Liu Y.; Liu J.; Chibwe L.; Wai Ng K.T.; Uchida Y.
21	Emerging Trends in the Valorization of Agricultural Waste and Their Utilization in Agricultural, Pharmaceuticals, and Environmental Cleanup	Yadav V.K.; Sharma A.K.; Gacem A.; Pandit J.; Wany A.; Kumar A.; Arshad M.; Alreshidi M.A.; Punetha V.D.; Mola Al Mesfer M.K.; Yadav K.K.; Dhingra H.K.; Egbosiuba T.C.; Patel A.; Choudhary N.

22	Agroecology and circular food systems: decoupling natural resource use from rural development in sub-Saharan Africa?	van Rooyen A.; Bjornlund H.; Moyo M.; Pittock J.; Parry K.; Mujeyi A.
23	A comprehensive review on agricultural waste utilization through sustainable conversion techniques, with a focus on the additives effect on the fate of phosphorus and toxic elements during composting process	Xu Q.; Zhang T.; Niu Y.; Mukherjee S.; Abou-Elwafa S.F.; Nguyen N.S.H.; Al Aboud N.M.; Wang Y.; Pu M.; Zhang Y.; Tran H.T.; Almazroui M.; Hooda P.S.; Bolan N.S.; Rinklebe J.; Shaheen S.M.
24	Circular Economy for the Sustainable Disposal and Reuse of Pruning Waste for Generating New Selective Materials	Shwartz G.; Oron G.
25	Development of sustainable biopolymer-based composites for lightweight applications from agricultural waste biomass: A review	Phiri R.; Mavinkere Rangappa S.; Siengchin S.; Oladijo O.P.; Dhakal H.N.
26	Rethinking food waste: Exploring a black soldier fly larvae-based upcycling strategy for sustainable poultry production	Mlambo V.; Dibakoane S.R.; Mashiloane T.; Mukwevho L.; Wokadala O.C.; Mnisi C.M.
27	Recycling food and agriculture by-products to mitigate climate change: a review	Rashwan A.K.; Bai H.; Osman A.I.; Eltohamy K.M.; Chen Z.; Younis H.A.; Al-Fatesh A.; Rooney D.W.; Yap P.-S.
28	Toward a Greener Future: Applying Circular Economy Principles to Saudi Arabia's Food Sector for Environmental Sustainability	Almulhim A.I.
29	Exploring the 5Rs Holistic Model for Zero Food Waste in Saudi Arabian Food Service Outlets	Sobaih A.E.E.; Abu Elnasr A.E.
30	Inferences on bioengineering perspectives and circular economy to tackle the emerging pollutants	Aneesh E.M.; Anoopkumar A.N.; Madhavan A.; Sindhu R.; Binod P.; Kuddus M.; Ruiz H.A.; Pandey A.; Awasthi M.K.; Show P.L.
31	Transitioning opportunities for sub-Saharan Africa's small-scale urban pig farming towards a sustainable circular bioeconomy	Mathobela R.M.; Molotsi A.H.; Marufu M.C.; Strydom P.E.; Mapiye C.
32	Pakistan's circular bio-economy: potential, opportunities and sustainable development	Ali Y.; Sabir M.; Afridi S.; Ullah Z.

33	Waste management and green technology: future trends in circular economy leading towards environmental sustainability	Tanveer M.; Khan S.A.R.; Umar M.; Yu Z.; Sajid M.J.; Haq I.U.
34	An Overview and Categorization of the Drivers and Barriers to the Adoption of the Circular Economy: A Systematic Literature Review	Pasqualotto C.; Callegaro-De-Menezes D.; Schutte C.S.L.
35	Enhancing the economic potential of organic waste by co-composting using ratio modelling toward a circular economy	Ofei-Quartey M.N.L.; Appiah-Effah E.; Akodwaa-Boadi K.; Ampaw B.; Taylor T.S.; Millogo Z.E.N.
36	Co-digestion of cow manure and food waste for biogas enhancement and nutrients revival in bio-circular economy	Abbas Y.; Yun S.; Mehmood A.; Shah F.A.; Wang K.; Eldin E.T.; Al-Qahtani W.H.; Ali S.; Bocchetta P.
37	Intelligent approaches for sustainable management and valorisation of food waste	Said Z.; Sharma P.; Thi Bich Nhung Q.; Bora B.J.; Lichtfouse E.; Khalid H.M.; Luque R.; Nguyen X.P.; Hoang A.T.
38	Modelling circular supply chains as an approach for waste management: A systematic review and a conceptual framework	Mahmoud H.A.; Essam S.; Hassan M.H.; Sobh A.S.
39	Circular economy business models as pillars of sustainability: Where are we now, and where are we heading?	Hina M.; Chauhan C.; Sharma R.; Dhir A.
40	Opportunities, challenges and trade-offs with decreasing avoidable food waste in the UK	Patel S.; Dora M.; Hahladakis J.N.; Iacovidou E.
41	Drivers and barriers of circular economy business models: Where we are now, and where we are heading	Hina M.; Chauhan C.; Kaur P.; Kraus S.; Dhir A.
42	Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management	Rashid M.I.; Shahzad K.
43	Effectiveness of ecotechnologies in agriculture for the recovery and reuse of carbon and nutrients in the Baltic and boreo-temperate regions: A systematic map	MacUra B.; Piniewski M.; Księżniak M.; Osuch P.; Haddaway N.R.; Ek F.; Andersson K.; Tattari S.

44	Circular economy business models and operations management	Lopes de Sousa Jabbour A.B.; Rojas Luiz J.V.; Rojas Luiz O.; Jabbour C.J.C.; Ndubisi N.O.; Caldeira de Oliveira J.H.; Junior F.H.
45	Recent advances on organic biofertilizer production from anaerobic fermentation of food waste: Overview	Areeshi M.Y.

CHAPTER 5

5 Legal and regulatory requirements

This chapter corresponds to the following phase and DSR step, as seen in the Table 5 snippet.

Phase	Objective	Research Method	Thesis Chapter
Phase 1 - Identification of (DSR 3)	Determine the legal and operational aspects of a circular economy model using legal documents.	Review legal literature	Chapter 4 - 5

5.1 Introduction

The implementation of a circular economy (CE) model within a protected ecotourism reserve in South Africa is subject to an interwoven framework of national environmental legislation, biodiversity protection mandates, water governance protocols, and international best practice guidelines. This chapter identifies and interprets the legal requirements relevant to organic waste management, water reuse, compost production, and sustainable agriculture in conservation settings. Emphasis is placed on ensuring compliance with local legislation while aligning the intervention with internationally endorsed sustainability and biodiversity principles.

The chapter draws from five key South African legal instruments: the National Environmental Management Act (107 of 1998), the National Environmental Management: Waste Act (59 of 2008), the National Water Act (36 of 1998), the Fertilizers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (36 of 1947), and the National Environmental Management: Protected Areas Act (57 of 2003). These are contextualised within the objectives of the National Biodiversity Strategy and Action Plan (DEA, 2015) and aligned with global standards set by the International Union for Conservation of Nature (IUCN), International Association for Impact Assessment (IAIA), World Bank, United States Agency for International Development (USAID), European Union (EU), and the United States Environmental Protection Agency (US EPA). Table 11 summarises the high-level legal requirements for operating a CE on an ecotourism reserve in South Africa.

Table 11: Summary Table of Legal Requirements

Area of Compliance	Governing Legislation	Implication for CE Design
Waste hierarchy & composting	NEMWA (RSA, 2008); NWMS (DEFF, 2020)	Follow norms and standards for on-site composting; avoid pollution

Protected area activity	NEMPAA (RSA, 2003)	Align with PAMP and conservation goals; obtain management approval
Fertiliser and feed	FFARSR Act (RSA, 1947)	Register if outputs leave site; ensure biological safety
Wastewater reuse	NWA (RSA, 1998)	General Authorisation or WULA depending on volume/risk
Ethical principles	NEMA (RSA, 1998)	Apply precautionary and sustainability principles across system

The *National Environmental Management Act (107 of 1998)* (NEMA) (RSA 1998) provides cross-cutting environmental management principles, e.g., precaution, polluter-pays, waste minimisation, and participation. It guides the interpretation and application of other sectoral laws. The *National Environmental Management: Waste Act (59 of 2008)* (NEMWA) operationalises these NEMA principles for waste, aligning its objectives with NEMA section 2 and implementing them through the National Waste Management Strategy (NWMS), notably the waste hierarchy and a circular-economy orientation. In protected areas, the *National Environmental Management Protected Areas Act (57 of 2003)* (NEMPAA) sits alongside NEMA. It establishes conservation objectives and management planning (PAMPs), while NEMA's principles still govern how waste risks are avoided, minimised and remedied within those areas. Finally, water-related activities fall under the *National Water Act (NWA, 1998)*, whose authorisations are read in accordance with the same NEMA principles on pollution prevention and precaution. In practice, this means NEMWA and NWMS give effect to NEMA's waste principles, and NEMPAA contextualises their application within conservation objectives and governance arrangements specific to protected areas (Roos et al., 2023).

Two governance interfaces are essential in design. First, jurisdiction and service delivery: while national/provincial bodies or private authorities manage protected areas, municipalities are constitutionally mandated to provide waste services (collection/transport/disposal). In remote parks, capacity and distance often mean reserves must self-provide compliant services or contract them, with clear documentation when waste crosses the gate (manifests, safe-disposal certificates) (Roos et al., 2023). Second, conservation siting and risk governance: infrastructure for organics processing should be located for accessibility but outside sensitive habitats and buffers, with controls to prevent odour, leachate, vectors and litter (Roos et al., 2023). If side-streams (e.g., reclaimed water, biosolids) are reused, adopt product standards and monitoring commensurate with conservation sensitivity. Moreover, consistent with NEMWA and NWMS, source separation is a baseline obligation, and life-cycle reasoning applies: reuse/recycling/recovery should proceed only where demonstrably less resource-intensive and

environmentally harmful than disposal, given transport distances and market access typical of remote reserves (Roos et al., 2023). These linkages explain why the CE design must: (1) anchor waste operations in NEMA principles, (2) meet NEMWA and NWMS hierarchy and documentation norms, (3) conform to NEMPAA objectives/PAMPs in siting and operation, and (4) secure the appropriate NWA authorisations for any water reuse.

5.2 Applicable legal instruments

To avoid fragmenting the legal logic, this chapter applies a tiered architecture that clusters instruments by their normative force and function. Primary statutes set non-negotiable obligations; subordinate instruments and authorisations operationalise them; national policies and strategies indicate the direction of travel; international standards provide best-practice benchmarks; and site-level plans translate these into operational controls for protected areas.

- **Tier 1: Primary legislation (binding, cross-cutting and sectoral).**

- National Environmental Management Act (NEMA)
- National Environmental Management: Waste Act (NEMWA)
- National Water Act (NWA)
- National Environmental Management: Protected Areas Act (NEMPAA)
- Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (Act 36)

Application: Establish hard constraints and duties, e.g. waste minimisation, pollution prevention, protected-area purposes, feed/fertiliser safety. Where statutes overlap, apply *lex specialis*, e.g. NEMWA for waste, NWA for water uses, under the umbrella of NEMA principles.

- **Tier 2: Subordinate instruments and permissions (operational, enforceable).**

Regulations, Norms and Standards, General Authorisations/Water-Use Licences, municipal by-laws.

Application: Translate Tier-1 duties into process rules and permits (e.g., on-site composting standards, waste classification/manifesting, water reuse authorisations).

- **Tier 3: Policies and strategies (direction-setting).**

- National Waste Management Strategy (NWMS)
- National Biodiversity Strategy and Action Plan (NBSAP), provincial/municipal waste and biodiversity plans.

Application: Guide design choices and sequencing, e.g., waste hierarchy alignment, diversion targets, and biodiversity objectives, but do not substitute for Tier-2 permissions.

- **Tier 4: International standards and guidance (benchmarking).**

- IUCN/IAIA principles for protected-area management and impact assessment.

Application: Inform design conservatism and due diligence, e.g. siting buffers, product standards, and monitoring, especially where local rules are silent or permissive.

- **Tier 5: Site-level instruments (operational translation).**
 - Protected Area Management Plan (PAMP)
 - Environmental Management Programmes (EMPrs)
 - SOPs, monitoring plans, training and incident-response procedures.
- **Application:** Convert tiers 1-4 into layout, operating rules, records, and competencies.

Apply the tiers top-down in design, then bottom-up in verification, showing that site-level artefacts meet Tier-2 criteria and remain consistent with Tier-1 duties.

5.2.1 National Environmental Management Act (107 of 1998)

The National Environmental Management Act (NEMA) (RSA, 1998) is the overarching environmental framework. Section 2 sets out mandatory environmental management principles, including:

- Sustainable development
- Polluter-pays and preventative principles
- Intergenerational equity
- Integration and transparency

These principles apply to all decisions made under new laws and are the moral basis for CE implementation in protected areas. Projects should be planned to have the least impact on the environment, the most significant positive impact on society, and the best balance of ecosystems (DR-LEG-001). To demonstrate that NEMA's principles of integration and openness are being applied, it is recommended to provide evidence of clear, open decision-making that allows everyone to participate (RC-LEG-001).

5.2.2 National Environmental Management: Waste Act (59 of 2008)

The NEMWA (RSA, 2008) establishes the legal foundation for classifying, storing, reusing, recycling, and treating waste in South Africa. Section 17 promotes the waste management hierarchy, which prioritises waste avoidance, followed by reuse, recycling, recovery, and finally, disposal as a last resort (DR-LEG-002). This hierarchy directly supports CE interventions.

Activities such as on-site composting and greywater reuse must comply with National Norms and Standards for the Storage of Waste (GN 926 of 2013) and the Norms and Standards for Organic Waste Composting (GN 561 of 2022). These standards stipulate containment requirements, buffer zones, leachate control, and recordkeeping provisions.

GN R.926 of 2013 - Storage of Waste

This regulation provides prescriptive requirements for the design and operation of waste storage facilities include:

- Impermeable floors and chemically resistant surfaces (DR-LEG-003).
- A secondary containment system capable of holding either 110% of the largest container or 25% of total volume (whichever is greater) (DR-LEG-004).
- Site placement away from sensitive areas, with buffer zones of 100 m in non-industrial areas (DR-LEG-005).
- Controlled drainage with a minimum freeboard of 0.5 m (DR-LEG-006).
- Restricted access, multilingual hazard signage, and regular leak inspections (DR-LEG-007).

Facilities storing any quantity of general or hazardous waste must register with the competent authority at least 90 days prior to construction (DR-LEG-008). These provisions ensure that all composting substrates, digestate, and organic residues are stored in compliance with pollution prevention and occupational safety standards (RSA, 2013).

GN R.561 of 2022 - Composting of Organic Waste

The new regulation states that composting facilities processing less than 10 tonnes of waste per day don't need a licence if they register with the government and comply with technical standards. Key provisions include:

- Registration with DFFE is supported by an Environmental Management Plan (EMP) and municipal approvals (DR-LEG-010).
- Feedstock classification, e.g. garden waste, food waste, manure, and corresponding composting technology, e.g. aerobic static piles or windrows (DR-LEG-011).
- Strict operating conditions covering odour management, fire control, temperature regulation, moisture monitoring (<40%), and leachate prevention (DR-LEG-012).
- Standard Operating Procedures (SOPs) and training requirements for all staff handling waste (DR-LEG-013).
- Regular audits, performance monitoring, and corrective action protocols (DR-LEG-014).

Although small-scale units (<10 t/day) may not be covered directly, they must still comply with Section 2 of NEMA regarding the duty of care and environmental protection (DEFF, 2022) (DR-LEG-015). Table summarises the technical requirements relevant to the storage and composting of organic waste.

Table 12: Technical Requirements for Storage and Composting of Organic Waste

Norm / Standard	Applicable Activities	Key Requirements	Implications for CE Model
GN R.926 of 2013	Storage of organic waste, compost, or digestate	Impermeable flooring, containment bunds, access control, signage, registration	All on-site storage facilities must be properly designed and documented.
GN R.561 of 2022	Composting >10 t/day of organic waste	EMP, feedstock classification, moisture/temp control, SOPs, audits	Even smaller systems must align with safe practices and duty-of-care principles

5.2.3 National Environmental Management: Protected Areas Act (57 of 2003)

The National Environmental Management: Protected Areas Act (NEMPAA) (RSA, 2003) regulates all land-use and commercial activities within designated protected areas. Section 50 permits the use of biological resources if it is (a) in accordance with the Protected Area Management Plan (PAMP) and (b) consistent with the reserve's ecological objectives.

Management must approve CE practices such as organic composting, BSFL rearing, and effluent reuse, and these practices must be clearly included in the PAMP. These activities must not harm biodiversity, introduce invasive species, or pollute sensitive ecosystems (RSA, 2003). Depending on their size, infrastructure, and ecological sensitivity, these interventions may also require approval from internal environmental authorities.

5.2.4 Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (36 of 1947)

This Act (RSA, 1947) controls the use of compost, insect-based feed, or digestate in farming. The Registrar must register compost to be sold or given away outside the project site, and it must be labelled in accordance with the rules. The utilisation of food waste as a feedstock through Black Soldier Fly Larvae (BSFL) or analogous methodologies necessitates compliance with established nutrient safety and contamination thresholds, particularly when employed within livestock systems. Conversely, when these organic materials are utilised on-site within a closed-

loop system, such as cycling from garden to compost and returning to the garden, registration may not be required. However, adherence to hygiene protocols and safe handling practices remains imperative.

5.2.5 National Water Act (36 of 1998)

Water reuse is regulated under the National Water Act (RSA, 1998). Section 21 defines “water use” to include discharge, reuse, storage, and irrigation of greywater and treated effluent. Small-scale wastewater reuse systems, e.g. wetland filtration or hydroponic reuse, may be authorised under the General Authorisation (GN 665 of 2013), provided they meet water quality and volume thresholds. Larger or sensitive applications may require a complete Water Use Licence Application (WULA) via the Department of Water and Sanitation.

Systems reusing greywater for irrigation or aquaponics must comply with microbiological and chemical quality limits to protect crops, soils, and downstream ecosystems.

5.2.6 National Waste Management Strategy (2020)

The National Waste Management Strategy (NWMS) (DEFF, 2020), issued under NEMWA, expands the operationalisation of the waste hierarchy by integrating CE principles into national policy. It identifies “waste as a resource” as a strategic goal and encourages innovation in waste beneficiation at the community level, including composting, insect farming, and decentralised resource recovery. Furthermore, it promotes integration with informal sectors and nature-based solutions, validating the use of compost and BSFL systems in rural conservation areas.

5.2.7 Integration of Biodiversity and Protected Area Governance

The design of circular systems in protected areas must be compatible with biodiversity conservation mandates. The National Environmental Management: Biodiversity Act (NEMBA, 2004) (RSA, 2004) and the National Biodiversity Strategy and Action Plan (DEA, 2015) mandate that any development in ecologically sensitive areas must contribute to ecosystem integrity, not merely avoid harm.

Best practice guidelines from the IUCN, IAIA, USAID, World Bank, EU, and US EPA recommend:

- Minimising waste leakage and nutrient overload.
- Avoiding interference with natural hydrology or faunal behaviour.
- Using nature-based solutions, e.g. wetlands, composting, bioswales, where possible.
- Ensuring transparency, benefit sharing, and inclusive governance.

These principles are particularly relevant when CE interventions involve converting food waste, organic matter, or water into on-site resources, such as food gardens, animal feed, or irrigation systems.

5.3 Chapter summary

While South African laws do not specifically require "circular economy" practices, they set standards for facilities that can fit into such systems. The National Environmental Management: Waste Act, the National Water Act, and the National Environmental Management: Protected Areas Act govern organic waste management, including composting, animal by-products, and effluent storage/use. Compliance with these laws and related standards facilitates legitimate waste-to-resource conversion, such as compost and treated water, while aligning with biodiversity and ethical governance goals in protected areas. Table 13 below consolidates all binding legal requirements.

Table 13: Legal/policy code register (LEG) summary

Code	Tier	Instrument / clause	Normalised requirement	Activity affected
DR-LEG-001	T1	NEMA s2	Duty of care; prevent pollution; minimise impacts; integrate social benefits; transparency	Whole system
RC-LEG-001	T1	NEMA s2	Document participatory process/public-interest benefits	Whole system
DR-LEG-002	T1	NEMWA s17	Apply waste hierarchy (avoid>reuse>recycle>recover>dispose)	All waste ops
DR-LEG-003	T2	GN R.926 (2013)	Impermeable, chemically resistant floors for waste storage	Storage
DR-LEG-004	T2	GN R.926 (2013)	Secondary containment ≥110% largest container or ≥25% total volume	Storage
DR-LEG-005	T2	GN R.926 (2013)	Site buffers (100 m in non-industrial areas)	Storage
DR-LEG-006	T2	GN R.926 (2013)	Controlled drainage; ≥0.5 m freeboard	Storage
DR-LEG-007	T2	GN R.926 (2013)	Restricted access; multilingual signage; routine leak inspections	Storage
DR-LEG-008	T2	GN R.926 (2013)	Register storage facility ≥90 days before construction	Storage

DR-LEG-010	T2	GN R.561 (2022)	Register composting facility; EMP; municipal approvals	Composting
DR-LEG-011	T2	GN R.561 (2022)	Declare feedstock classification and composting technology	Composting
DR-LEG-012	T2	GN R.561 (2022)	Operate with odour/fire control, temperature regulation, moisture monitoring, and leachate prevention	Composting
DR-LEG-013	T2	GN R.561 (2022)	Maintain SOPs and staff training for waste handling	Composting
DR-LEG-014	T2	GN R.561 (2022)	Audits, performance monitoring and corrective action (CAPA)	Composting
DR-LEG-015	T1/T2	NEMA s2 + GN R.561	<10 t/day systems: duty of care and safe-practice controls still apply	Small composting

The register defines two compliance layers: (1) NEMA/NEMWA fundamentals (DR-LEG-001, -002) that set the duty of care and the waste hierarchy across the whole system, and (2) prescriptive Tier-2 norms for storage (GN R.926: DR-LEG-003-008) and composting (GN R.561: DR-LEG-010-014), with duty-of-care explicitly binding for small (<10 t·day⁻¹) facilities (DR-LEG-015). For design, these map directly to artefacts: registration letters and EMP/approvals; storage pad specs (floors, bunds, buffers, drainage, access/signage); operating logs (temperature, moisture, odour, leachate) and SOPs and training records. For verification, each DR-LEG has an auditable evidence item, enabling an unambiguous pass/gap judgement.

CHAPTER 6

6 Theoretical model

Phase	Objective	Research Method	Thesis Chapter
Phase 2 – Design (DSR 3-4)	Design a theoretical circular economy model, mapping process flows, material exchanges, and key performance indicators.	Industrial engineering modelling tools, e.g., MFA and VSM.	Chapter 6-7

6.1 Introduction

This chapter elaborates on the theoretical model of the circular economy, which synthesises the technical, environmental, and legal prerequisites identified through a comprehensive scoping review and thorough legal analysis. This aligns with Step 3 of the Design Science Research Methodology (DSRM), wherein the artefact is developed in response to a specified problem environment (Peffer et al., 2007). The model is conceptualised as a systems-based configuration illustrating the valorisation and recirculation of organic waste streams within a decentralised, closed-loop agri-food system, particularly suitable for ecotourism and conservation contexts.

The artefact is derived exclusively from the existing literature and the codes delineated in preceding phases. This methodological approach ensures that the artefact's structure is aligned with scientifically validated and regulatory principles. The insights obtained from the scoping review guided the delineation of the model's subsystem boundaries, flow interactions, and loop-closure logic. The literature underscores the significance of implementing short-loop, decentralised processes, particularly in remote contexts (Masindi et al., 2022), as well as the necessity for integrated process control within agro-waste management systems (Dalto et al., 2024). Furthermore, it highlights the conceptualisation of biomass utilisation as cyclical nutrient processes rather than as linear terminal uses (Toplicean & Datcu, 2024). These collective insights facilitated a paradigm shift from a linear waste-processing chain to a network characterised by interlinked, self-sustaining flow systems.

6.2 Model architecture

The theoretical model is first presented visually to provide an overview of the system's main components and their interactions. The functional block diagram shown in Figure 7 illustrates the major waste generation nodes, the conversion and processing subsystems, the utilisation pathways, and the supporting infrastructure that together constitute the closed-loop agri-food

system. The purpose of the diagram at this stage is not to present a finalised artefact, but to serve as an orientation device that demonstrates the subsequent analysis of each subsystem component satisfying the system requirements from phase 1.

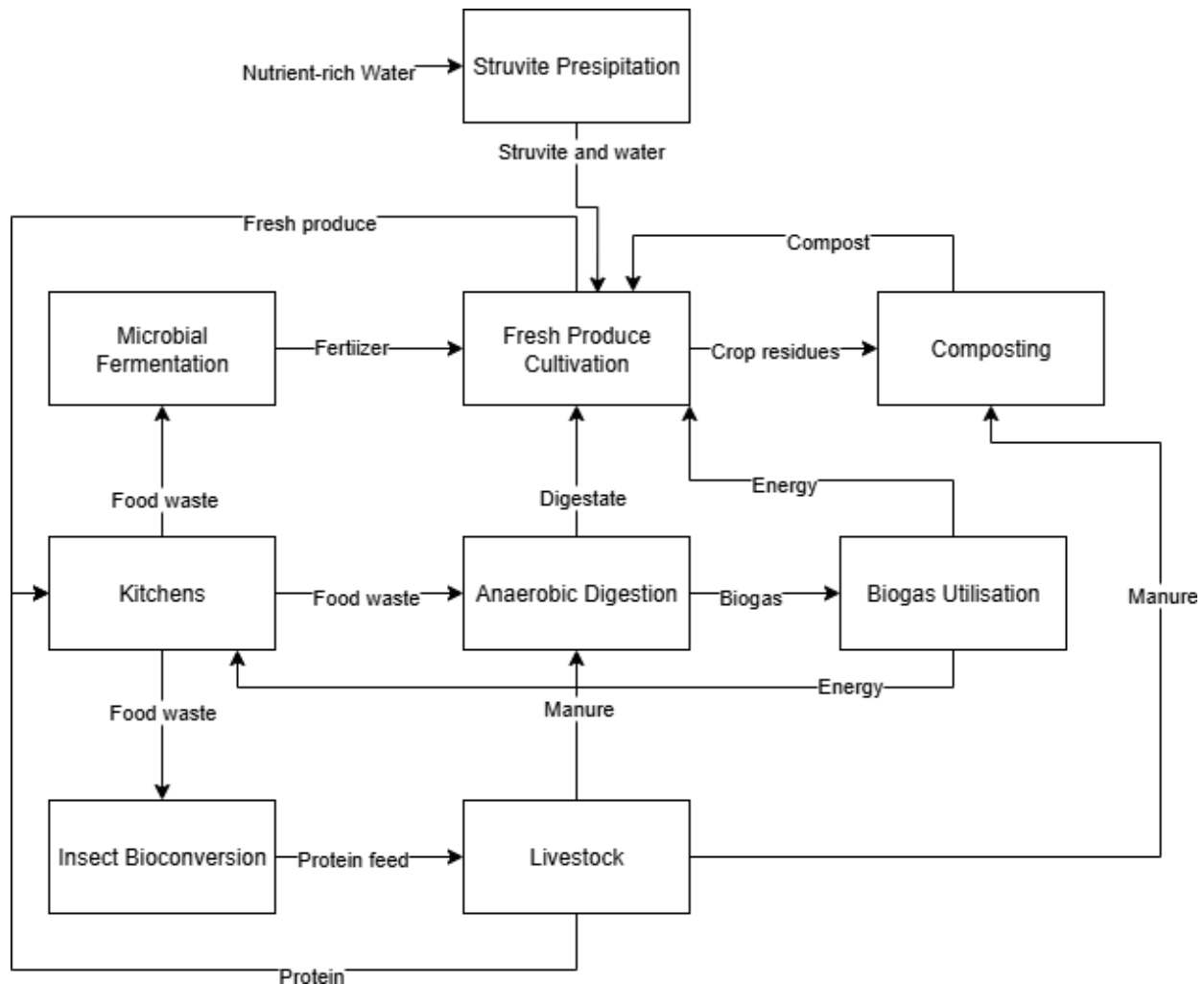


Figure 7: Functional block diagram of an example circular economy

The diagram emphasises the flow of material, energy, water and information between subsystems. At the input stage, organic waste arises predominantly from kitchens and restaurants as post-consumer food residues, and from cultivation activities as crop residues and non-usable produce. These streams are directed towards conversion subsystems such as microbial fermentation, composting, anaerobic digestion and insect bioconversion. Each of these processes produces outputs such as soil amendments, livestock feed, renewable energy, and secondary products like struvite fertiliser.

The outputs are reintegrated into productive systems, demonstrating the practical application of circularity concepts. Composting and fermentation processes generate soil amendments that are subsequently applied in agricultural practices to enhance nutrient cycling and soil health. The

protein-rich biomass derived from black soldier fly larvae serves as animal feed for poultry and swine, thereby reducing the dependency on external feed resources. Anaerobic digestion yields biogas, a renewable energy source, and digestate, which is utilised as a soil conditioner. Concurrently, the implementation of supportive infrastructure, such as water recycling and monitoring systems, can aid accurate, efficient, and sustainable operations.

The diagram visually integrates individual processes into a circular economy system. It serves as a reference for this chapter, discussing each node and flow related to the coded requirements, scoping review, and legal analysis, ensuring the model is conceptually consistent and aligned with design principles.

6.3 Design rationale and requirement basis

The formulation of the theoretical model is guided by the principles of Design Science Research (DSR). These principles mandate that the artefact be explicitly aligned with the problem's contextual parameters and the requirements established during the initial stages of the investigation. This section explains the rationale for the model's design and explains how the encoded requirements, derived from the scoping review and legal analysis, constitute the system's framework.

6.3.1 Alignment with Design Science Research Methodology

In the third step of the DSR methodology as delineated by Peffers et al. (2007), an artefact is conceptualised as a systems model. The model's structuring is informed by two complementary sources of evidence: (1) a scoping review that integrated technological, environmental, and operational insights pertinent to interventions in circular agriculture, and (2) a legal analysis that delineated the regulatory frameworks governing waste management, water recycling, fertilizer production, and operations within protected areas.

6.3.2 Requirement-driven design logic

The model, built on requirement codes from earlier phases (Tables 9 and 13), guides design decisions through grouped configuration recommendations, enablers, constraints, and legal obligations. These collectively define operational, environmental, and governance needs. Specific requirements, such as maintaining C: N ratios in composting (DR-LIT-101) and retention times in anaerobic digestion (DR-LIT-102), inform the subsystem's logic. Cross-cutting requirements, such as quality assurance and monitoring (DR-LIT-301; DR-LIT-405), ensure system coherence, making the model a defensible synthesis of evidence and regulations.

System requirements (DR codes)

These are rules that come from both laws and textbooks. They set the lowest acceptable quality and process standards for each technology. For instance, composting needs to maintain a stable C: N ratio, aeration, and moisture levels until it is ready (DR-LIT-101). Anaerobic digestion, on the other hand, requires set retention times and reports biogas yields (DR-LIT-102). Cross-cutting requirements include quality assurance, monitoring, and tracking circularity indicators such as nutrient recovery and diversion rates (DR-LIT-301; DR-LIT-405).

Resource configuration recommendations (RC codes)

Although these are not formalised regulations, they provide guidance on optimal system configuration. Some examples are preferring modular layouts when utilities are limited (RC-LIT-202), adding struvite to fertigation to replace new fertiliser inputs (RC-LIT-106), and creating short-loop feedbacks to reduce transfers and losses (RC-LIT-205). These suggestions are not required, but they do make the model more efficient and resilient, and they include them when they make sense.

Enablers (EN codes)

Adoption and sustained operation of technologies depend on enabling conditions, such as awareness- and engagement-based programmes to improve waste separation (EN-LIT-301), institutional support for scaling (EN-LIT-302), and governance capacity to monitor and ensure safe reuse (EN-LIT-304). These enablers do not alter technical design but create the conditions under which the system can function effectively.

Constraints (CN codes)

The literature underscores persistent obstacles that influence the development of viable design strategies. Among these are seasonal variations in waste quantities, which necessitate the inclusion of buffer capacity (CN-LIT-302), constraints in technical expertise that demand both targeted training and the adoption of simplified technologies (CN-LIT-303), and substantial initial investments that require the adoption of phased implementation methodologies (CN-LIT-304). Furthermore, the reliability of the output is limited by the heterogeneity of the raw organic materials.

Legal requirements (LEG codes)

Statutory provisions impose mandatory conditions that cannot be bypassed. At the system level, the duty of care and pollution prevention under the National Environmental Management Act (DR-

LEG-001) and the waste hierarchy prescribed by NEMWA (DR-LEG-002) are binding. Specific operational controls apply to storage (DR-LEG-003-008) and composting facilities (DR-LEG-010-014), including feedstock declaration, odour and fire management, leachate prevention and routine audits. Even small-scale systems below regulatory thresholds remain subject to duty-of-care obligations (DR-LEG-015).

These clusters work together to create the design logic of the theoretical model. The DR and LEG codes set mandatory limits, while the RC, EN, and CN codes determine how the system is set up and changed to fit its operational context. This approach, based on requirements, ensures that the artefact is both theoretically sound and evidence-based, with compliance in practice.

6.4 Components of the theoretical model

The theoretical model is organised into four main component groups: waste generation nodes, conversion and processing subsystems, utilisation pathways, and supporting infrastructure. Each group is described below in relation to the requirement codes that informed its inclusion and configuration.

6.4.1 Waste generation nodes

Organic waste originates from two primary sources: food preparation and consumption in kitchens and restaurants, and cultivation activities such as vegetable production. The inclusion of these nodes reflects system requirements for source separation and contamination control at the point of collection (DR-LIT-201), supported by behavioural enablers that emphasise participation and awareness (EN-LIT-301). Legal obligations under NEMWA further enforce the waste hierarchy, requiring that avoidance, reuse and recycling are prioritised before disposal (DR-LEG-002). Recognising seasonal variability and infrastructure constraints (CN-LIT-302; CN-LIT-305), the model assumes that waste quantities fluctuate and must be buffered to maintain continuity in downstream processes.

6.4.2 Conversion and processing subsystems

The central design feature of the model is the transformation of organic waste into usable products through a set of complementary processes:

- **Composting and microbial fermentation.** These are organic amendments that have been stabilised. Composting must follow specific process controls (DR-LIT-101; DR-LEG-012) and registration requirements (DR-LEG-010). Fermentation, on the other hand, is a low-emission, nutrient-preserving option. This node is also shaped by suggestions for aerated static piles in low-labour situations (RC-LIT-101) and controls for smells and fires (DR-LEG-012).

- **Anaerobic digestion.** This process generates both biogas and digestate. Minimum standards require defined retention times and reporting of specific yields (DR-LIT-102; DR-LIT-402), with digestate reuse conditioned by quality assurance (DR-LIT-301). Legal obligations reinforce the safe management of storage and by-products (DR-LEG-003–006). Resource configuration recommendations encourage the use of locally produced biogas to minimise transport and shorten loops (RC-LIT-102).
- **Black soldier fly larvae (BSFL) bioconversion.** BSFL units convert food residues into protein and frass. Requirements emphasise hygiene, odour, vector control, and the quality of frass before soil application (DR-LIT-103; DR-LIT-403). Integration into feed systems also aligns with recommendations to co-manage food waste with manures to optimise recovery (RC-LIT-107).
- **Nutrient and material recovery.** Struvite precipitation and, where feasible, pyrolysis or hydrothermal carbonisation, allow targeted recovery of nutrients and bio-based materials. Each process is bound by requirements for process control, product characterisation and safe reuse (DR-LIT-104–106; DR-LIT-404). Recommendations encourage integrating struvite into on-site fertigation (RC-LIT-106) and the dual use of biochar as both a soil conditioner and a filtration medium (RC-LIT-104).

Collectively, these conversion nodes are configured in modular form, as recommended for contexts with infrastructure limitations (RC-LIT-202), while legal obligations ensure that facilities operate under safe storage, drainage, and monitoring conditions (DR-LEG-003-007).

6.4.3 Utilisation and output pathways

The processing subsystems send recovered products to nearby sinks to close loops and reduce the need for external inputs. Compost, fermentation, and digestate are used on growing areas to make the soil more fertile and improve nutrient cycling (DR-LIT-204). BSFL protein is added to the diets of pigs and chickens, and struvite is used instead of chemical fertilisers in fertigation systems (RC-LIT-106). Biogas produced via anaerobic digestion is prioritised for on-site thermal utilisation, aligning with guidelines for short-loop energy integration (RC-LIT-102). Legal requirements for safe land application of recovered products (DR-LEG-001; DR-LEG-002) support these use pathways and must meet quality assurance standards before use in soils or food chains (DR-LIT-301).

6.4.4 Supporting infrastructure and enablers

Supporting systems ensure the model runs smoothly. Water recycling and controlled drainage meet the needs for leachate management and environmental protection (DR-LEG-006; RC-LIT-104). Monitoring, training and routine audits are prescribed for composting facilities (DR-LEG-

013-014) and extended across all nodes through quality assurance requirements (DR-LIT-203; DR-LIT-301). Engagement and awareness programmes (EN-LIT-301), institutional support (EN-LIT-302) and governance capacity (EN-LIT-304) act as enablers of responsible operation. Constraints such as high upfront costs (CN-LIT-304) are mitigated through phased deployment, while infrastructure gaps (CN-LIT-305) are addressed by modular design and redundancy.

6.4.5 Summary of requirements for traceability

The requirement traceability for each subsystem is summarised in Table 10. This table consolidates the system requirements, configuration recommendations, enablers, constraints and legal obligations into a single overview. The purpose of this synthesis is to demonstrate how each component of the theoretical model is anchored in explicit codes.

Table 10: Summary of subsystem components and associated requirement clusters

Subsystem/ Component	System requirements	Configuration recommendations	Enablers	Constraints	Legal requirements
Waste generation nodes	DR-LIT-201 (source separation, contamination)	-	EN-LIT-301 (awareness, participation)	CN-LIT-302 (seasonal variability), CN- LIT-305 (infrastructure gaps)	DR-LEG-001 (duty of care), DR-LEG-002 (waste hierarchy)
Composting / Bokashi	DR-LIT-101, DR-LIT-401 (process control, KPIs)	RC-LIT-101 (aerated piles), RC-LIT-205 (short loops)	EN-LIT-301 (training/awareness)	CN-LIT-303 (skills), CN-LIT- 304 (finance)	DR-LEG-010- 015 (registration, controls, SOPs, audits)
Anaerobic digestion (AD)	DR-LIT-102, DR-LIT-402 (HRT/SRT, yields)	RC-LIT-102 (local heat use)	EN-LIT-303 (technology appropriateness)	CN-LIT-302 (load swings), CN-LIT-304 (phased roll-out)	DR-LEG-003- 006 (storage, containment, drainage)
BSFL bioconversion	DR-LIT-103, DR-LIT-403 (hygiene, frass quality)	RC-LIT-107 (co- manage with manures)	EN-LIT-301 (engagement for separation)	CN-LIT-303 (skills, training)	DR-LEG-001- 002 (duty of care, waste hierarchy)
Nutrient recovery	DR-LIT-104– 106, DR-LIT- 404	RC-LIT-104 (dual use of biochar), RC-LIT- 106 (fertigation)	EN-LIT-302 (institutional support)	CN-LIT-305 (infrastructure),	DR-LEG-001- 002 (duty of care, hierarchy)

Subsystem/ Component	System requirements	Configuration recommendations	Enablers	Constraints	Legal requirements
(struvite, HTC, biochar)	(process/product quality)			CN-LIT-304 (finance)	
Utilisation pathways	DR-LIT-204 (routing outputs to sinks), DR- LIT-301 (QA before reuse)	RC-LIT-106 (fertigation integration), RC-LIT- 205 (short transfer)	EN-LIT-302 (institutional support for uptake)	CN-LIT-302 (seasonal uptake variability)	DR-LEG-001- 002 (safe reuse, hierarchy)
Supporting infrastructure	DR-LIT-203 (operating controls), DR- LIT-405 (circularity KPIs)	RC-LIT-202 (modularity, local fit)	EN-LIT-304 (monitoring, governance capacity)	CN-LIT-305 (infrastructure gaps)	DR-LEG-006- 007 (drainage, access, signage)

By linking each subsystem to this balanced set of drivers, the theoretical model is shown to be both rigorous and adaptable. The tabulated traceability ensures that the development process is transparent and that subsequent verification can be systematically carried out against requirements established in earlier phases.

6.5 Integration and circular flows

While the preceding section examined each subsystem individually, the theoretical model derives its value from the way in which these components are integrated into a functioning whole. The system is designed to establish closed loops of material, energy, water and information, ensuring that organic waste is continuously transformed into productive inputs rather than being lost to disposal pathways.

6.5.1 Nutrient loop

Composting, fermentation, and anaerobic digestion turn organic waste from kitchens, restaurants, and farms into soil amendments, digestate, and struvite. These are returned to the fields where they were grown, closing the nutrient cycle between growing food and removing waste. Black soldier fly larvae also help by turning food waste into high-protein biomass for livestock and frass for soil conditioning, enabling nutrients to be returned in different ways.

6.5.2 Energy loop

Anaerobic digestion generates biogas prioritised for on-site thermal uses, such as cooking or heating water. This short-loop energy strategy reduces reliance on external fuels and exemplifies the circular economy principle of minimising transfer distances. In areas with sufficient infrastructure, producing biochar or hydrochar is another way to convert waste into energy, and the resulting solids help keep the soil healthy.

6.5.3 Water loop

Treatment and reuse systems include controlled drainage and leachate capture from composting, as well as greywater streams. The model reduces the need for fresh water by recirculating it for irrigation or processing. This is in line with legal requirements for pollution prevention and safe reuse. Biochar is also being considered as a means of filtering water, thereby improving both nutrient recovery and water quality.

6.5.4 Feedback and redundancy

The model incorporates multiple valorisation routes for each waste stream, enhancing its adaptive capacity under variable operating conditions. For example, food waste may be directed either to black soldier fly larvae (BSFL) conversion or to anaerobic digestion, depending on seasonal fluctuations in waste generation and operational priorities. This redundancy increases system resilience by ensuring that diversion targets can be maintained even when one subsystem functions below optimal capacity. The inclusion of buffer storage and modular layouts further enables dynamic adjustment to variations in feedstock volume and infrastructure availability, supporting continuous process stability and sustained circular performance.

6.5.5 Governance and monitoring

Overlaying these loops is a governance layer informed by both enablers and legal requirements. Engagement programmes and training ensure that waste is separated at source and directed to the appropriate subsystem, while routine monitoring and audits safeguard compliance. Circularity indicators, such as diversion rates, nutrient retention and substitution ratios, enable system performance to be tracked transparently.

From a systems engineering perspective, the model operates as a network of multiple conversion nodes and feedback loops that interact dynamically. This integration is what differentiates the artefact from a set of isolated technologies. By designing the flows to reinforce one another, the model establishes a circular supply chain that maximises resource efficiency, mitigates environmental impacts and adheres to statutory obligations.

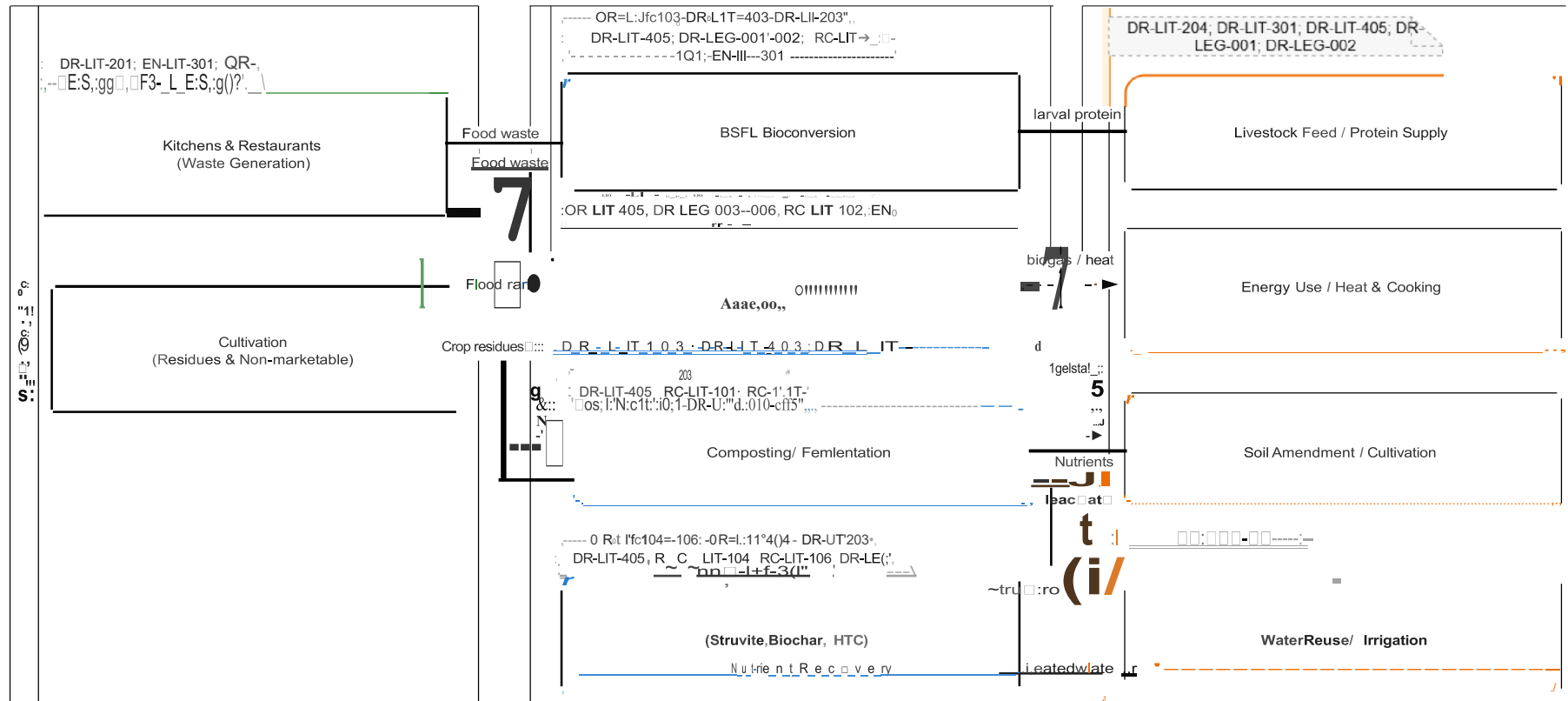
6.6 Consolidated theoretical model artefact

The preceding sections have delineated the discrete subsystems of the theoretical model and defined the interconnections among their respective flows of material, energy, water, and information. Collectively, these elements constitute the integrated artefact that signifies the primary deliverable of Phase 2 of the research design. Figure 8 illustrates the Systems Modelling Language (SysML) block diagram of the model, encompassing nodes for waste generation, processing modules, utilisation sinks, and the corresponding DR/RC/EN/LEG requirement codes at their designated points of application.

Model Overview

The Figure 8 is systematically organised into three vertical columns, each symbolising a functional layer within the circular system framework: Layer 1 (L1): Waste Generation (depicted in green) involves hospitality operations such as kitchens and restaurants, as well as cultivation activities that generate streams of organic waste and crop residues. Layer 2 (L2): Processing Modules (illustrated in blue) encompass the conversion technologies that facilitate the stabilisation or transformation of organic waste. These modules include a) BSFL (Black Soldier Fly Larvae) bioconversion, b) Anaerobic digestion, c) Composting/fermentation and d) Nutrient-recovery processes, including struvite precipitation, biochar production, and hydrothermal carbonisation. Layer 3 (L3): Utilisation Sinks (represented in orange) where the outputs of the processing modules are directed towards productive applications such as livestock feed, energy production, soil amendment, and water reuse.

Food waste valorisation system



Legend

— Material / Nutrient

-- -- Water / Aqueous

- - - - Energy (biogas heat)

Figure 8 Theoretical CE model

The model illustrates a closed-loop system connecting waste generation, conversion, and use. Organic waste from hospitality and agriculture is processed in treatment units to produce soil amendments, larval protein, biogas, or nutrient-rich water. These are then used for livestock feed, horticulture, energy, and irrigation. The system's redundancy manages variable waste and seasonal changes. A governance layer ensures that circularity indicators support adaptive management measures in terms of compliance and performance. Training and support are included for consistent operation. This model integrates evidence-based requirements from reviews, offering a system for circular-economy efforts in ecotourism and conservation.

Figure 9 adapts the Ellen MacArthur Foundation's (2019) butterfly diagram to visualise the biological loops of the consolidated theoretical circular economy model.

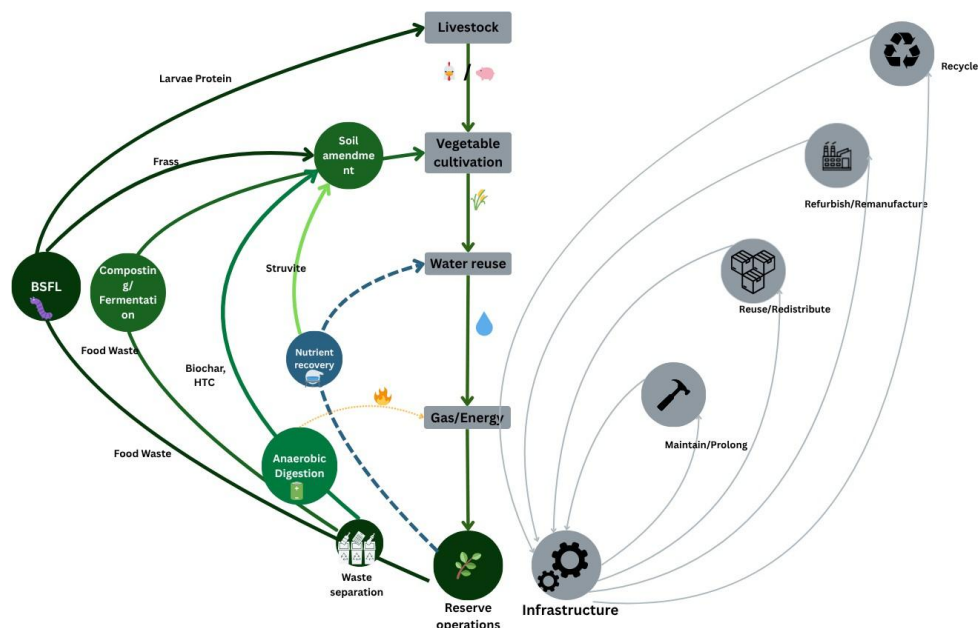


Figure 9 Butterfly diagram of the theoretical CE model

The green wing on the left illustrates the biological cycle, which constitutes the central component of the food-waste valorisation system. Organic waste from kitchens, restaurants, and agricultural activities undergoes a series of cascading processes: bioconversion using black soldier fly larvae (BSFL), anaerobic digestion, composting and fermentation, and nutrient recovery. These processes extract any remaining biological or energetic value before reintegrating the materials into productive use.

The diagram shows the system's progressive value retention. BSFL bioconversion turns food waste into larval protein for livestock feed, linking nutrient recovery to animal production. Anaerobic digestion produces biogas and digestate for renewable energy and soil amendment. Composting and fermentation stabilise organic waste, enriching soils for vegetable cultivation. Nutrient-recovery processes yield struvite, biochar, and hydrothermally carbonised material for mineral supplements and filtration media. Treated effluent and leachate circulate in the water-reuse loop, maintaining productivity in arid environments.

Reserve operations integrate biological subsystems to coordinate outputs such as livestock feed, energy, soil amendments, and irrigation water, thereby reducing reliance on external inputs. The grey right wing symbolises the technical cycle, focusing on material retention through maintenance, reuse, refurbishment, and recycling. While secondary to biological loops, it underscores long-term material stewardship in reserve operations.

The butterfly diagram shows the transformation of a linear waste path into a regenerative system through biological and technical strategies, embodying circularity principles: maintaining resource value, minimising waste, and regenerating ecological capital within a decentralised eco-tourism setting.

6.7 Chapter summary

Phase 2 has produced a consolidated theoretical model artefact that formalises a circular food waste valorisation system suitable for ecotourism and conservation contexts. The artefact was derived exclusively from coded evidence and obligations, with system requirements (DR), configuration recommendations (RC), enabling conditions (EN), contextual constraints (CN), and legal requirements (LEG) embedded at their points of application. Presented as a SysML-style internal block diagram, the model preserves end-to-end traceability from requirement codes to system structure and interfaces.

The system integrates waste-generation nodes with modular processing options: composting/fermentation, anaerobic digestion, insect bioconversion, and nutrient recovery, and with utilisation sinks for soils, energy, feed, and water. Material, energy and water loops are intentionally short, favouring on-site use and proximate routing, while a governance layer provides duty of care, monitoring, quality assurance and corrective action. Assumptions are explicit: source separation and contamination control at collection; compliant storage and pre-processing; operational controls and KPIs for each node; and system-level circularity indicators (diversion, nutrient retention, substitution) to support transparent performance management.

Design choices emphasise regulatory compliance, resource efficiency and operational resilience. Modularity and buffers address seasonal variability and infrastructure gaps; technology appropriateness and training provisions mitigate skills constraints; and phased deployment acknowledges financing realities. None of these elements depend on site-specific data: the artefact is a requirement-driven, generalisable specification that can be specialised without altering its governing logic.

CHAPTER 7

7 Contextual adaptation and pilot data acquisition at the Kalahari Reserve

This chapter corresponds to the following research phase and DSR step, as seen in the Table 5 snippet.

Phase	Objective	Research Method	Thesis Chapter
Phase 2 – Design (DSR 3-4)	Design a theoretical circular economy model, mapping process flows, material exchanges, and key performance indicators.	Industrial engineering modelling tools, e.g., MFA and VSM.	Chapter 6-7

7.1 Introduction

The purpose of this chapter is to adapt the theoretical circular economy model, developed in phase 2, to the case context of The Kalahari Reserve at a decentralised scale, and to instantiate instrumented pilot modules that enable systematic data acquisition. This chapter implements step 4 of the DSR: demonstrating the artefact in a relevant setting to show feasibility. These pilot studies provide empirical records of subsystem performance, forming the empirical basis for DSR 5 (evaluation) that entails verification (Phase 3) and validation (Phase 4).

7.2 Site context and design constraints

The Kalahari Reserve is a remote luxury eco-tourism and conservation site situated in the arid Northern Cape of South Africa. Ecological sensitivity, climatic extremes, logistical isolation, and a service-based workforce characterise its operational conditions. These attributes directly shape the feasibility of decentralised circular food-waste valorisation pilots. They are therefore mapped here against the enabling (EN) and constraining (CN) codes established in phase 1 of this study.

7.2.1 Utilities and infrastructure

The reserve is not connected to municipal waste services, and the grid electricity supply is prone to fluctuations and is therefore supplemented with solar power and generators. Although The Reserve has access to the Kalahari pipeline, which supplies water from the Orange River, water resources are carefully managed in line with its conservation culture. These factors impose infrastructure and resource constraints (CN-LIT-305) that restrict the technical set of feasible subsystems. At the same time, logistical isolation reinforces the need for short loops that valorise waste locally, reducing reliance on external disposal or imports (RC-LIT-205; DR-LIT-204).

7.2.2 Climate and seasonality

The Kalahari climate is characterised by large temperature swings between day and night, very hot summers, and unpredictable rainfall. This kind of change affects fermentation speed, manure drying rate, and feed conversion efficiency. It is a systemic constraint (CN-LIT-302) that requires flexible storage and buffer space to handle seasonal changes.

7.2.3 Skills-based

Most personnel at the reserve are trained primarily in conservation and hospitality, with limited technical proficiency in operating bioconversion technologies. This constraint narrows the range of feasible technology configurations (CN-LIT-303) but simultaneously presents an opportunity for local institutions to enhance human capacity through targeted training, risk management, and vocational development programmes (EN-LIT-304). Beyond initial competency development, sustained operations depend on effective knowledge retention and management systems that capture, codify, and disseminate operational expertise. Structured documentation, standard operating procedures, and mentoring mechanisms are therefore required to preserve institutional memory, ensure continuity during staff transitions, and support iterative improvement of the circular valorisation system (Argote and Miron-Spektor, 2011; Lieder and Rashid, 2016).

7.2.4 Logistical isolation

The Reserve's remoteness from regional towns makes off-site disposal costly and environmentally undesirable. The absence of nearby support services further underscores the role of infrastructure gaps (CN-LIT-305) and also strengthens the case for closed-loop subsystems that valorise on-site waste (RC-LIT-205; DR-LIT-204).

7.2.5 Permitting and governance

All pilot activities are subject to South African environmental and waste legislation. The National Environmental Management Act (NEMA) and the National Environmental Management: Waste Act (NEMWA) provide overarching obligations. At the same time, GN R.561 of 2022 establishes norms and standards for composting and fermentation, and GN R.926 of 2013 regulates the handling and storage of animal by-products. The reserve is a protected area run by a private organisation. It must follow specific rules for storage (DR-LEG-003-008) and composting and fermentation (DR-LEG-010-015). Ethical obligations concerning animal welfare and conservation integrity impose additional constraints on viable subsystem designs.

To operationalise the contextual constraints and enablers identified at the organisation, the site factors were systematically mapped against the relevant codes in Table 7. This ensures that subsequent subsystem adaptation is grounded in traceable boundary conditions.

Table 7 Site context mapped against EN and CN codes

Site factor	Description	EN/CN code mapping
Utilities and infrastructure	No municipal waste services; limited and variable energy and water supply	CN-LIT-301; CN-LIT-302
Climate and seasonality	Wide diurnal ranges; high summer temperatures; erratic rainfall	CN-LIT-303
Skills base	Staff trained for hospitality/conservation; limited technical capacity	CN-LIT-304 (constraint); EN-LIT-304 (training enabler)
Logistical isolation	Long distance to towns; costly off-site disposal	CN-LIT-301; RC-LIT-205; DR-LIT-204
Governance and permitting	NEMA; NEMWA; GN R.561 (2022); GN R.926 (2013); duty of care obligations	DR-LEG-001/002; DR-LEG-003-008; DR-LEG-010–015

This mapping demonstrates that the pilot system at The Reserve is shaped by infrastructural scarcity, climatic extremes and workforce characteristics, but also by opportunities to embed training and localised loops as strategic enablers. These contextual features serve as the boundary conditions for subsystem adaptation.

7.3 Adaptation of the theoretical model to The Reserve

The theoretical model developed in phase 2 encompassed a wide range of potential valorisation nodes, including anaerobic digestion, black soldier fly larvae (BSFL) rearing, struvite recovery, hydrothermal carbonisation, and biochar production. When screened against the contextual conditions at The Reserve, only a subset of these technologies could be instantiated on a decentralised pilot scale. This is owed to the design constraints professed in section 7.2.

Anaerobic digestion and hydrothermal carbonisation are examples of capital-intensive technologies that were left out because of gaps in infrastructure and funding (CN-LIT-304; CN-LIT-305). BSFL systems, though promising, were excluded at this stage due to hygiene and odour control requirements, as well as the necessity for reliable frass quality monitoring (DR-LIT-103; CN-LIT-303), which surpassed the reserve's technical capacity. Nutrient recovery

technologies, such as struvite precipitation and biochar production, were also not allowed due to current permitting conditions and site-readiness issues (DR-LIT-106; DR-LIT-104; CN-LIT-305).

In contrast, pigs, chickens, food waste separation, and bokashi fermentation were all closely aligned with the reserve's operational goals and the factors that enabled them. These subsystems were chosen for their relatively low cost, ease of training, and potential to produce immediately usable outputs (feed substitution, manure, compost), while still meeting the regulatory obligations outlined in Table 13. Their configurations are described in the subsections below, with explicit traceability to (DR), configuration recommendations (RC), enabling factors (EN), constraints (CN), and legal requirements (LEG).

7.3.1 Pig subsystem

Role and function: The pig subsystem was initially included in the theoretical model (Chapter 6) as a key pathway for valorising food scraps into protein and manure. At The Reserve, a herd of six pigs was maintained in an outdoor pen with shaded feeding and watering areas, capable of holding up to ten animals. The intended outputs were edible protein for staff consumption and manure/bedding for subsequent use in composting or fermentation.

Configuration: The pigs were housed in a fenced enclosure with a concrete watering trough and partial roofing for shade. The floor was composed of loose Kalahari sand, which influenced manure management. Feeding occurred twice daily using food scraps from hospitality and lodges, logged to allow substitution ratios to be calculated.

Observed outcome: Despite the theoretical expectation of manure production, collection proved impractical under site conditions. The sandy substrate absorbed moisture, dispersing and disintegrating faeces. Dung beetle activity further removed the remaining matter. Consequently, there was no substantial accumulation of manure available for downstream processing. This difference shows a limitation that was not anticipated in the theoretical design: pigs were able to eat food scraps, but they did not produce a recoverable manure stream under the conditions present.

Applicable codes:

- Diversion of organic waste into animal feed: DR-LIT-101; DR-LIT-204.
- Integration of co-feeding strategies: RC-LIT-107.
- Duty of care and biosecurity for animal by-products: DR-LEG-010; GN R.926 (2013).
- Constraint: lack of recoverable manure due to sandy substrate and natural scavenging activity (CN-LIT-302; CN-LIT-305).

Operational controls: Pigs were fed twice a day and received only food scraps from the kitchens, totalling about 525-700 kg per week. This fits with the goals of diversion and substitution (DR-LIT-101; DR-LIT-204; RC-LIT-107). A concrete trough provided water on demand and was refilled as needed. Weekly pen cleaning was done without disinfectants or extra bedding because the sandy substrate made it hard to do so (CN-LIT-305).

Daily logs were kept to record the amount of feed given and the herd's basic observations. This met the requirement for documented operating controls (DR-LIT-203). To lower biosecurity risks, staff who handled food scraps and worked in the enclosure wore protective clothing. The chicken subsystem was also physically separated from the pigs, which is a safe way to raise animals (EN-LIT-304; DR-LEG-010).

Training: Personnel were instructed in the safe management of food waste for porcine alimentation and in the accurate monitoring of the quantity of food allocated to the pigs (EN-LIT-304). Within the observed conditions, instruction on manure collection was deemed unnecessary.

7.3.2 Chicken subsystem

Role and function: The chicken subsystem provides a secondary pathway for valorising food scraps, consuming fractions unsuitable for pigs, and thereby reducing overall food waste. Outputs are eggs for consumption and litter/manure that could, in principle, be incorporated into downstream composting or fermentation.

Configuration: A flock of 25 chickens was housed in mobile coops used for sleeping, with outdoor access during the day. The enclosure floor was sandy, similar to the pig subsystem, and included drinking water troughs. The housing and pen design allows for expansion to a maximum of 50 birds. Feeding was carried out exclusively with food scraps, amounting to 50-75 kg per week.

Observed outcome: While the chickens successfully consumed food scraps, the sandy substrate limited manure accumulation, as faeces quickly dispersed and were removed by beetle activity. Consequently, litter and manure collection were negligible during the pilot.

Applicable codes:

- Diversion of organics into feed (DR-LIT-101; DR-LIT-204).
- Integration of waste streams into fertilisation pathways (RC-LIT-201; RC-LIT-205).
- Legal requirements for storage and safe handling of animal by-products (DR-LEG-003-008).
- Constraint: sandy substrate and insect activity preventing recovery of manure (CN-LIT-302; CN-LIT-305).

Operational controls: Feeding was undertaken 2-3 times a week using only food scraps, with an approximate weekly intake of 50-75 kg. Water troughs were refilled as needed. Cleaning was performed weekly, with no bedding or disinfectants used. Daily records were kept of feed volumes (DR-LIT-203). Staff wore protective clothing, and the chicken subsystem was physically separated from pigs to prevent cross-contamination (EN-LIT-304; DR-LEG-010).

Training: Staff were trained in the safe handling of food scraps, routine cleaning, and basic flock health monitoring (EN-LIT-304).

7.3.3 Food-waste generation and source separation

Role and function: The kitchens, restaurants, and staff village constitute the principal nodes of food-waste generation at The Reserve. These streams provide the feedstock for downstream valorisation via pigs, chickens, and bokashi fermentation. Effective source separation at both nodes is essential to minimise contamination and ensure safe routing of organics into recovery pathways.

Configuration.

Two separate collection systems were in place:

- **Hospitality kitchens and restaurants.** Dedicated bins for organics, recyclables, and contaminants were provided. Food waste was weighed in kitchens before disposal, and the cumulative monthly weight is shown in Figure 10, which indicates seasonal fluctuations in guest numbers. Most food scraps were fed to pigs and chickens.

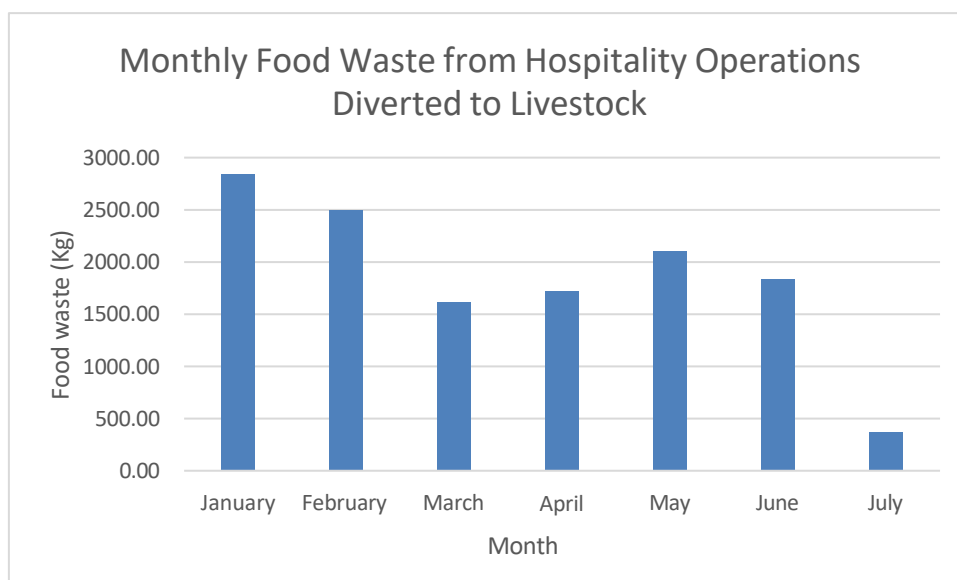


Figure 10 Monthly Food Waste from Hospitality operations diverted to livestock

- **Staff village.** Food waste is recorded every other day and totalled monthly (see Figure 11). Though currently sent to a landfill, it is intended for bokashi fermentation for use in a vegetable garden.

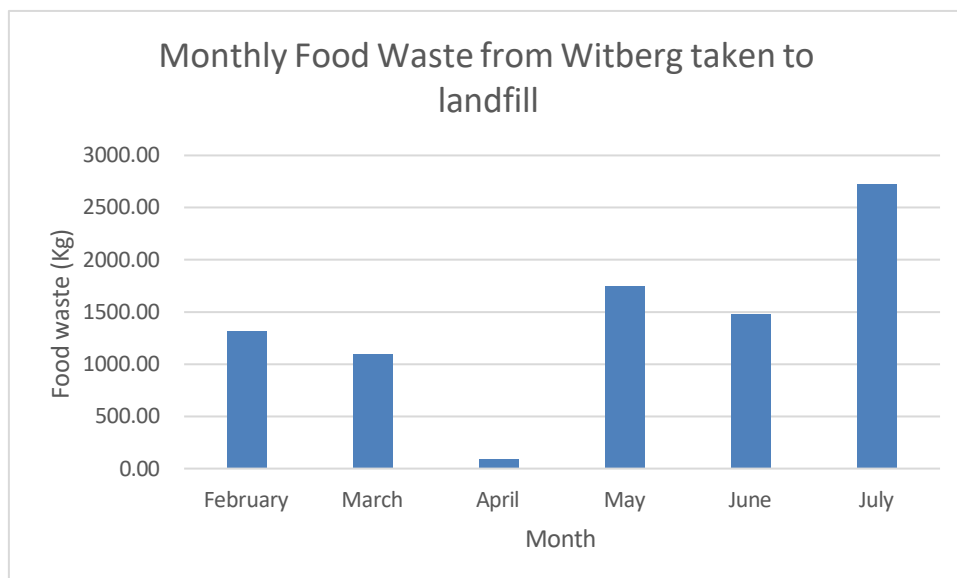


Figure 11 Monthly Food Waste from the village taken to the landfill

Observed outcome: Hospitality operations generated higher total volumes, but staff-village collections were more regularised through scheduled pick-ups. Together, these streams supplied the bulk of organic feedstock for the decentralised pilots. Contamination was minimal where signage and awareness were strong, though periodic audits indicated a need to reinforce training to sustain compliance.

Applicable codes:

- Source separation at collection is a mandatory design requirement (DR-LIT-201) and a legal obligation under the duty of care provisions (DR-LEG-001/002).
- Staff and visitor awareness served as enablers of compliance (EN-LIT-301), while variability in guest numbers led to seasonal swings in hospitality volumes (CN-LIT-302).
- Proximity of waste streams to utilisation nodes supported loop-closure (DR-LIT-204; RC-LIT-205).
- Storage and handling of separated fractions were conducted in line with regulatory controls (DR-LEG-003-008).

Operational controls: At both nodes, bins were labelled to reduce contamination risk. Kitchen staff and village residents were instructed in proper separation, supported by visible signage. Hospitality bins were weighed daily, while village collections were logged every second day.

Weekly audits were conducted to assess contamination, and corrective actions were triggered when threshold levels were exceeded.

Training: Management develops targeted programmes for kitchen staff and waste collectors to ensure correct separation practices and compliance with the duty of care. Risk-governance measures such as protective clothing and safe handling procedures were embedded in standard operating protocols (EN-LIT-304).

7.3.4 Bokashi Fermentation

Role and function: Bokashi fermentation was implemented as a decentralised treatment pathway for food waste, providing an anaerobic route that stabilises organic matter while producing a nutrient-rich fermented substrate and liquid leachate. The intended outputs were (1) bokashi mass suitable for incorporation into soils or further composting, and (2) leachate requiring controlled management or further processing.

Configuration: The pilot was conducted with a sealed bokashi bin containing effective microorganisms. Before putting the food waste in the bin, it was weighed, and the inoculant was added in measured layers. To change the moisture content, dry fractions were added as needed. The bins were kept in the Kalahari's standard conditions and checked for pH and retention time. After the fermentation cycle was complete, mass balances were performed for the fermented matter and any leachate produced.

Observed outcome: The bokashi system ran four-week fermentation cycles. Table 8 shows the mass balance and performance indicators. It processed 10.32 kg of food waste and 260 g of bokashi bran, yielding 9.68 kg of fermented material (6.2% mass reduction) and 809 ml of leachate. The pH dropped to 4.03, indicating anaerobic acidogenesis. Weekly inputs of 2.2-2.9 kg suggest small batch operations. These figures serve as a baseline for flow visualisation in the MFA.

Table 8 Bokashi fermentation pilot: inputs and outputs (4-week cycle)

Item	Measurement	Comment
Food waste processed	10.32 kg	Total input over 4 weeks
Bokashi bran used	0.26 kg	Inoculant added to aid fermentation
Fermented output	9.68 kg	Final mass after 4 weeks
Mass change	-6.20%	Slight reduction from fermentation
Leachate collected	0.81 kg	Liquid produced during the process

Final pH	4.03	Expected acidic level for fermentation
Weekly input rate	2.2 - 2.9 kg per week	Operated in small, manageable batches

Applicable codes.

- Quality assurance before reuse (DR-LIT-301).
- Fermentation recipes and integration (RC-LIT-104).
- Duty of care and composting/fermentation norms (DR-LEG-010-015).
- Seasonal load swings necessitating buffer storage (CN-LIT-302).
- Infrastructure gaps limiting advanced monitoring (CN-LIT-305).

Operational controls: Calibrated scales were used to accurately measure the mass of both inputs and outputs. A handheld pH meter was used for continuous pH monitoring. The containment unit was maintained in a sealed condition to preserve anaerobic conditions and was accessed only weekly to add a new layer of waste and microorganisms. Personnel wore protective clothing during the handling of the fermenting waste to ensure safety and maintain the integrity of the experimental process.

Training: Staff should be trained in preparation of feedstock, safe handling of fermented material, leachate management, and basic monitoring tasks (EN-LIT-304). Training should emphasise the importance of QA steps before any reuse of bokashi products, consistent with (DR-LIT-301).

7.4 Data processing and derived indicators

Basic monitoring instruments were deployed across the pilots to generate empirical records suitable for descriptive analysis. Calibrated digital scales were used for feed inputs and waste flows, and handheld pH meters were used for pH measurements. Leachate volumes were measured using measuring cups. Bin contamination audits were conducted visually. Data were recorded daily or weekly, depending on the subsystem, and later transcribed from logbooks into Excel.

The following descriptive indicators are derived from the pilot data streams:

- **Nutrient retention %** = $\frac{\text{nutrient mass retained in fermented bokashi or compostable product}}{\text{nutrient mass of feedstock}} \times 100$ (DR-LIT-301; DR-LIT-405).
- **Substitution ratios** = $\frac{\text{Virgin material avoided}}{\text{Baseline requirement}} \times 100$ (RC-LIT-202; RC-LIT-107; DR-LIT-405).

- **Volume reduction % (bokashi)** = $\frac{\text{input mass} - \text{output mass}}{\text{input mass}} \times 100$ (DR-LIT-301).
- **Leachate yield** = $\frac{\text{leachate volume}}{\text{input mass}}$ (L/kg) (DR-LIT-301).
- **Bokashi compost application** = 2 kg/m² of cultivation soil at a depth of 30-40 cm below the surface.
- **Livestock intake rates.**
 - **Pigs:** Six pigs consumed approximately 75-100 kg of food scraps per day, equivalent to 12.5-16.7 kg per pig per day. At full capacity (ten pigs), the subsystem could therefore process ~125-167 kg/day.
 - **Chickens:** A flock of 25 chickens consumed 50-75 kg of food scraps per week, equivalent to 0.29-0.43 kg per chicken per day. At full capacity (50 birds), the subsystem could process 100-150 kg/week. This range was treated as a uniform distribution.
 - **Subsystem capacity utilisation.** Intake rates also indicate utilisation relative to design capacity. For pigs, observed consumption accounted for 60% of the herd's potential capacity; for chickens, 50% of the flock's capacity. These figures inform calculations of feed substitution ratios (RC-LIT-202; RC-LIT-107; DR-LIT-405) and provide context for diversion percentages (DR-LIT-101).

These metrics provide a descriptive profile of pilot subsystem behaviour and establish the input dataset for validation in Phase 4 (see Table 9).

Table 9 Data dictionary for the reserve's pilot studies

Subsystem	Variable	Definition	Unit	Value (pilot)	Sampling frequency	Code linkage
Pigs	Pig feed input	Food scraps consumed by a herd of six pigs	kg/day	75-100	Daily	DR-LIT-101; DR-LIT-204
	Pig intake per animal	Feed input ÷ number of pigs	kg/pig/day	12.5-16.7	Daily	RC-LIT-202; RC-LIT-107
Chickens	Chicken feed input	Food scraps consumed by a flock of 25 chickens	kg/week	50-75	Weekly	DR-LIT-101; DR-LIT-204
	Chicken intake per bird	Feed input ÷ number of chickens	kg/chicken/day	0.29-0.43	Weekly	RC-LIT-202; RC-LIT-107

Food-waste generation	Hospitality FW mass	Organic waste from kitchens/restaurants (Livestock.xlsx)	kg/month	Jan: 2,836; Feb: 2,494; Mar: 1,610; Apr: 1,722; May: 2,104; Jun: 1,830; Jul: 366	Daily log, monthly total	DR-LIT-201; DR-LEG-001/002
	Village FW mass	Food waste collected from the staff village (every second day)	kg/month	Feb: 27.1; Mar: 863.3; Apr: 761.2; May: 2,769.1; Jun: 1,482.9; Jul: 4,436.2; Sep: 597.6; Nov: 640.2; Dec: 576.0	Collection log, monthly total	DR-LIT-201
Bokashi	Input mass	Total food waste placed in the bin	kg	10.32	Weekly log	DR-LIT-301; DR-LEG-010
	Inoculant used	Bokashi bran added to the waste	25g/kg	260	Weekly	RC-LIT-104
	Retention time	Duration of fermentation cycle	days	14	Per cycle	DR-LEG-012
	Output mass	Fermented product mass	kg	9.68	Per cycle	DR-LIT-301
	Volume reduction	$(\text{Input} - \text{output}) \div \text{input} \times 100$	%	6.2	Per cycle	DR-LIT-301
	Leachate yield	Leachate produced per kg of FW	L/kg	0.078	Per cycle	DR-LEG-012
	Final pH	Bokashi pH at the end of the cycle	pH	4.03	Per cycle	DR-LIT-301
Garden trial	Compost soil application	Bokashi compost incorporated at 2 kg/m ² , 40 cm depth	kg/m ²	2	Before each planting season	DR-LIT-204
	Compost soil effect	Observed outcome of bokashi compost applied to garden soil	Qualitative	Improved soil performance	During cultivation and after harvest	DR-LIT-204
	Leachate aeroponic effect	Observed outcome of concentrated leachate applied in aeroponic towers	Qualitative	Inhibited plant growth	During cultivation	DR-LIT-301

	Nitrification requirement	Literature-informed QA step for leachate before aeroponic reuse	Not measured	Nitrification + micronutrients required	Research-informed	DR-LIT-301; RC-LIT-104
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Table 9 puts the measured and observed variables from the pilots into a data dictionary. The values show that pigs and chickens ate a lot of the food scraps that were thrown away every day and every week. The logs from the hospitality and staff village showed that waste generated varied greatly from season to season. The bokashi pilot produced quantitative records of input mass, inoculant dosing, leachate production, and pH, which served as the basis for quality assurance indicators. Observations from the garden trial showed that compost improves soil health, but leachate needs to be nitrified and micronutrients added before it can be reused in aeroponics. The table as a whole provides a clear dataset that supports the descriptive indicators in this chapter and supports the modelling in phase 4: Validation.

7.5 Garden trial observations

A small-scale garden trial was undertaken to observe the agronomic performance of bokashi outputs. Two application routes were tested: bokashi compost applied to soil, and bokashi leachate applied directly in aeroponic towers.

Observed outcome.

- Bokashi compost improved soil performance and was compatible with the reserve's objectives for nutrient cycling (DR-LIT-204).
- Bokashi leachate, when applied at concentrated doses in aeroponic towers, inhibited plant growth.
- Bergstrand et al. (2020) stated that bokashi leachate requires nitrification and micronutrient supplementation to be effective in hydroponic or aeroponic systems (DR-LIT-301; RC-LIT-104). This nitrification was not tested in the pilot, making it a research-based recommendation rather than a proven result. Supporting this, Tong et al. (2021) found poorer growth in a 10% bokashi hydroponic medium compared with conventional methods, likely due to lower levels of essential nutrients such as nitrate, iron, and magnesium ($p \leq 0.05$). Lind (2014) noted that nitrogen in bokashi leachate is mostly in ammonium form before nitrification, which may hinder plant uptake without further processing.

Applicable codes

- Quality assurance before reuse (DR-LIT-301).

- Training and risk-governance for handling leachate (EN-LIT-304).
- Processing adaptation and integration (RC-LIT-104; RC-LIT-106).

The observations highlight the potential of bokashi compost for soil-based systems and identify a quality assurance gap for leachate in soilless applications.

7.6 Governance, compliance and risk controls

Governance of the pilot studies was designed to ensure alignment with South African environmental legislation, as established in phase 1, and the operational realities of a conservation setting. At the pilot scale, the emphasis was placed on ensuring that decentralised operations complied with minimum statutory thresholds, that risks were systematically identified and mitigated, and that personnel were adequately trained to manage organic waste streams safely.

7.6.1 Legal compliance

Pilot activities were subject to the duty of care obligations under the National Environmental Management Act (DR-LEG-001) and the waste hierarchy principles of the National Environmental Management: Waste Act (DR-LEG-002). The storage and handling of food waste and animal by-products were regulated by GN R. 926 of 2013. Bokashi fermentation was governed by GN R.561 of 2022, which mandates registration, declaration of feedstocks, odour and fire control, leachate prevention, and SOP-based monitoring (DR-LEG-010-015). Even at capacities below 10 t/day, small-scale systems remained bound by duty-of-care provisions (DR-LEG-015).Standard operating procedures and monitoring

SOPs were established for feed handling, bin separation, bokashi inoculation, leachate capture, and safe application of composted products. Staff training was carried out to ensure familiarity with monitoring routines (EN-LIT-304). Monitoring covered feed and waste weights, contamination rates and bin pH, and leachate volumes. Records were logged daily or weekly, depending on the subsystem, to fulfil documentation requirements (DR-LIT-203; DR-LEG-013-014).

7.6.2 Risk register

To ensure safe operation of the decentralised pilots, a structured risk register was compiled and provided in Table 10. The register identifies operational, environmental, health and safety, and compliance risks specific to The Reserve's context. Each entry is linked to the relevant design, legal, enabling, and constraining codes, ensuring full traceability and regulatory alignment.

Table 10 Risk register

Category	Risk description	Likelihood	Impact	Mitigation	Risk rating	Code linkage
Operational	Contamination of food-waste streams with plastics, metals or glass	Medium (2)	High (3)	Source separation at collection, staff training, weekly audits, and corrective actions	Moderate (6)	DR-LIT-201; EN-LIT-301; DR-LEG-001/002
Operational	Failure to recover manure due to sandy substrate and dung beetle activity in pig/chicken enclosures	High (3)	Medium (2)	Consider design modifications (concrete slab or bedding)	Moderate (6)	CN-LIT-302; CN-LIT-305
Operational	Seasonal variability in hospitality waste volumes leading to under-utilisation of subsystems	High (3)	Medium (2)	Implement buffer storage; staggered feeding/fermentation schedules	Moderate (6)	CN-LIT-302; RC-LIT-205
Environmental	Leachate discharge from bokashi bins contaminates the soil	Medium (2)	Low (1)	Capture leachate in sealed containers; ensure controlled disposal; future nitrification QA for reuse.	Low (2)	DR-LIT-301; DR-LEG-012; RC-LIT-104
Environmental	Odour and pest attraction around waste storage or fermentation sites	High (3)	Low (1)	Maintain sealed containers; weekly cleaning; cover storage areas	Low (3)	DR-LEG-012; CN-LIT-302
Health & Safety	Risk of staff exposure to pathogens during waste handling	Medium (2)	High (3)	Provide protective clothing, hygiene training, and SOP compliance checks.	Moderate (6)	EN-LIT-304; DR-LEG-013

Health & Safety	Heat build-up in fermenting material creates a fire hazard	Low (1)	High (3)	Monitor bin temperatures weekly; avoid overfilling; provide shaded storage.	Low (3)	DR-LEG-012; DR-LIT-301
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Compliance	Failure to maintain accurate records of waste inputs/outputs	Medium (2)	Medium (2)	Daily logbooks; Excel transcriptions; periodic supervisor audits	Moderate (4)	DR-LIT-203; DR-LEG-013–014
Compliance	Non-registration of fermentation/storage facilities under GN R.561 (2022) and GN R.926 (2013)	Medium (2)	Medium (2)	Ensure all pilot facilities are declared; retain documentation of approvals.	Moderate (4)	DR-LEG-008; DR-LEG-010–011
Compliance	Misapplication of bokashi leachate in aeroponic systems without QA	Medium (2)	Medium (2)	Explicitly restrict use to soils unless nitrification and micronutrient supplementation are implemented.	Moderate (4)	DR-LIT-301; RC-LIT-104

The table shows that feed diversion to pigs, chickens, and bokashi was successful, but local conditions, such as sandy soil and seasonal changes in waste streams, posed risks. Environmental risks focused on managing leachate and preventing pest infestations, while health and safety risks highlighted the importance of staff training and protective gear. To avoid compliance risks, such as maintaining accurate records and complying with GN R.561 (2022) and GN R.926 (2013), constant supervision is required. The register emphasises the need for robust SOPs, clear monitoring protocols, and flexible management to safeguard both environmental quality and system integrity.

7.6.3 Governance summary

At pilot scale, governance emphasised the proportional application of statutory requirements to small, decentralised operations, combined with low-technology monitoring and risk-based SOPs. The system thereby ensured that the pilots operated within the reserve’s infrastructural constraints (CN-LIT-305) while still meeting duty of care obligations and maintaining safety and environmental integrity.

7.6.4 Sustainability objectives in context

The theoretical circular economy model is based on the sustainability goals for protected areas under Section 17 of NEMPAA 2003. These goals require ecotourism sites to balance environmental protection with quality visitor experiences and socio-economic viability, conserving biodiversity and functioning as systems providing environmental goods and services for sustainable livelihoods.

Within this legislative context, the model contributes directly to several of NEMPAA's core objectives by protecting ecological integrity and conserving biodiversity through the diversion of organic waste from landfills, preventing contamination of soils, water, and habitats, ensuring the sustained supply of environmental goods and services via the recovery and reuse of nutrients, water, and biomass within on-site cycles, thereby maintaining soil fertility and reducing external resource extraction, providing for the sustainable use of natural and biological resources by valorising waste streams into feed, compost, and renewable energy that support self-sufficient operations, rehabilitating and restoring degraded ecosystems through the return of stabilised organic matter to soils and the regeneration of biological productivity, and contributing to human, social, and economic development by creating opportunities for local employment, training, and innovation in sustainable waste management and agro-ecological practices.

The model converts NEMPAA's broad policy goals into measurable sustainability metrics: waste-diversion, nutrient-retention, water-reuse, and resource-substitution rates. Integrating these into daily reserve operations makes eco-tourism a practical conservation tool, aligning economic activity with ecological stewardship.

7.6.5 Valorisation in context

At the organisation, valorisation turns organic waste from hospitality and staff operations into resources for on-site food production, reducing environmental impact. In remote conservation areas with limited waste-management options, it serves as both a sustainability and resilience strategy.

The valorisation system's core includes three pathways: Livestock feeding uses consumer food waste for pigs and chickens, reducing landfill waste and linking hospitality kitchens to internal food supply through animal protein. Bokashi fermentation processes non-feed waste anaerobically using bokashi bran, creating nutrient-rich compost for soil improvement and aligning with ecosystem rehabilitation goals. Vegetable cultivation uses bokashi compost and livestock manure to enhance soil, returning nutrients to the biosphere and supplying fresh produce to hospitality.

These three pathways form a biological loop where food waste becomes feed, feed produces animal protein, and fermented organic matter enhances soil fertility. This system turns ecological liabilities into assets, aligning reserve operations with conservation, sustainable resource use, and ecological integrity.

This localised valorisation demonstrates the efficacy of circular-economy principles at a micro-scale when optimised through appropriate technological advancements and behavioural modifications. It establishes a foundational model for integration by quantifying the synergies among livestock, bokashi, and horticulture, thereby unlocking the system's potential.

7.7 Integration and data flow for The Reserve's pilots

The five subsystems piloted at The Reserve: pigs, chickens, food-waste generation and separation, garden trails and bokashi fermentation, were configured to demonstrate short-loop resource cycling under decentralised conditions. Integration was guided by the principle that outputs must be routed to proximate sinks and that short feedback loops must be prioritised. In line with enabling conditions, subsystem design emphasised modularity and appropriateness, while acknowledging that seasonal variability and infrastructure gaps define the operational boundary conditions.

The hospitality kitchens and the staff village constitute the primary waste-generation nodes. Food scraps are collected every second day in the village and daily in the hospitality units, in accordance with contamination control requirements. These scraps are then partitioned into two flow pathways: direct feeding to livestock (pigs and chickens) and diversion to bokashi fermentation. The livestock, therefore, act as biological processors, converting kitchen discards into meat protein and manure, although sandy soils and beetle activity prevented manure accumulation during this phase of the pilot. Residual fractions and surplus scraps unsuitable for livestock were directed to a bokashi bin, and the surplus was still sent to landfill at this point. The bokashi subsystem produced two outputs: solid fermented compost and liquid leachate.

Figure 12 shows the material flow analysis (MFA) of the organisation's pilot system, showing food waste from kitchens and a village of staff directed to pigs, chickens and bokashi containers. It also illustrates the use of bokashi compost and leachate in a vegetable garden for nutrient recovery trials. The system is a loose circular model, closing some loops locally, but having outputs and leakages outside the regenerative cycle. Food waste re-enters the food chain as meat and eggs, while bokashi compost enhances garden soil fertility, forming short biological loops. However, landfill disposal, nutrient volatilisation, and unused leachate prevent full closure. This decentralised circularity, with partial recovery and internal reuse, suits small, remote operations and offers functional circularity at a pilot scale. It highlights areas for future

improvement, like complete leachate reuse and a scaled garden to achieve a more self-sustaining loop.

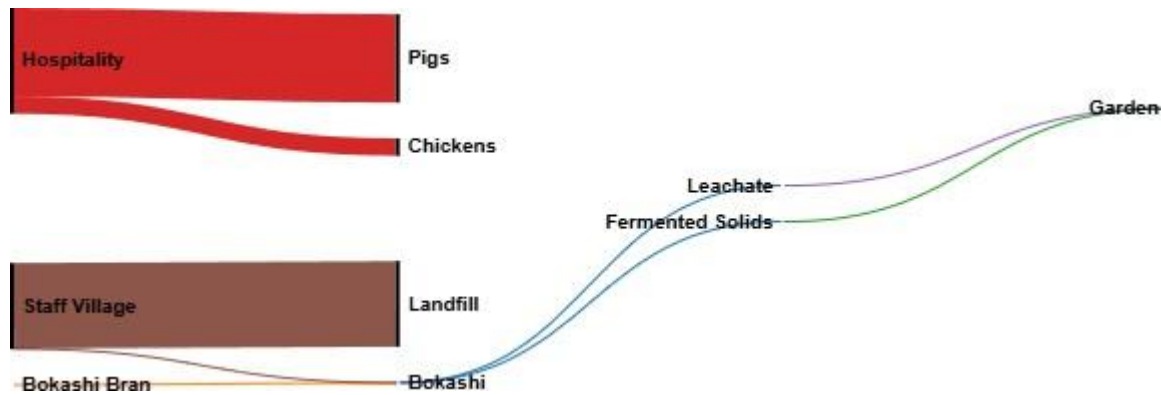


Figure 12 MFA of The reserve's instantiation created in Rawgraphs.io.

The material flow analysis shows how organic waste and resource streams were routed during the organisation's pilot study. In hospitality, kitchens were the primary source of food waste, which was sent to pigs and chickens. Most of the waste from the staff village was sent to a landfill. Bokashi fermentation worked as a separate system that turned the inputs into fermented solids and leachate, both of which were used in the experimental garden.

At this point in the pilot study, the garden did not produce enough food to feed the kitchens or the staff village. This means that, even though valorisation loops have begun, the cycle is still incomplete when it comes to integrating food back into the food service system. Also, the flows of livestock (pigs and chickens) were not yet set up to work as continuous feedback loops. The pigs are only slaughtered at the end of their expected lifespan, and the people who cared for them are responsible for selling the meat. The same applies to the chickens. As a result, the MFA shows possible early-stage circularity, where materials are being diverted, but the full loop closure into the human food supply chain has not yet occurred.

While bokashi composting proves effective at the micro scale, it requires upscaling to manage the entire staff village's waste output adequately. A large portion of food waste currently goes directly to landfill sites. To enhance the circularity of the waste management system, it is imperative to expand the bokashi process so that the organic refuse from the staff village is consistently stabilised through fermentation rather than discarded. However, augmenting the bokashi system's capacity without a corresponding increase in output channels may result in a downstream bottleneck. The resultant fermented solids and leachate require effective utilisation. Hence, it is crucial to expand gardening or associated agricultural systems alongside bokashi concurrently. This strategy will ensure that bokashi compost and leachate are converted into

valuable outputs, thereby completing the nutrient cycle and providing fresh produce to the reserve's culinary operations.

The pilot project established circularity in the reserve's food system by integrating hospitality kitchens, livestock feeding, bokashi fermentation, and soil-based cultivation. Organic waste was transformed into feed and compost, proving the feasibility of low-tech solutions in remote areas. This setup lays the groundwork for tighter nutrient loops. To achieve full nutrient cycling, future efforts should scale up the bokashi system for staff village waste and expand the garden to use the compost, enhancing nutrient capture and sustainability.

7.8 Chapter summary

This chapter applied DSR Step 4 by adapting the Phase 2 circular-economy model to a Kalahari Reserve's eco-tourism context and creating pilot modules for data capture. Context analysis identified key conditions: arid climate, seasonality, infrastructure scarcity, isolation, workforce skills, and regulatory requirements under NEMA/NEMWA and GN R.561 (2022)/GN R.926 (2013) linked to the study's codes (DR/RC/EN/CN/LEG) for traceability.

The technology screening identified three viable subsystems: livestock feeding (pigs, chickens) for food scraps, bokashi fermentation for stabilisation, and vegetable cultivation as a nutrient sink. More resource-heavy options were excluded. Pilots using standard procedures showed that pigs and chickens consumed much of the hospitality food waste. Still, manure recovery was minimal due to sandy soils and the presence of dung beetles. The bokashi pilot demonstrated nutrient recovery and soil-amending potential. Garden trials showed benefits, but concentrated leachate required nitrification and micronutrients. Operations adhered to standards, and a material-flow analysis confirmed the system's circularity, highlighting areas for improvement. Chapter 7 confirms feasibility, offers data, and establishes baselines for future phases.

CHAPTER 8

8 Verification

This chapter corresponds to the following research phase and DSR step, as seen in the Table 5 snippet.

Phase	Objective	Research Method	Thesis Chapter
Phase 3 - Verification (DSR 5)	Verify that the conceptual model adheres to all identified technical, environmental, legal, and operational.	Criteria compliance assessment and SEQUAL	Chapter 8

This chapter implements Phase 3 of the study, which aligns with Step 5 (Evaluation) in DSR Methodology. The objective of this phase is to ascertain the internal consistency, semantic precision, and organisational alignment of the CE model before its external validation. Within the DSR process, verification constitutes the systematic evaluation of an artefact's internal quality, its coherence, completeness, and adherence to design and contextual requisites, whereas validation, conducted subsequently, assesses the artefact's external functionality under simulated or real-world conditions (Hevner et al., 2004, Peffers et al., 2007, Venable et al., 2016).

The Semiotic Quality Framework (SEQUAL) is a model-verification framework rooted in semiotic theory, the study of signs, meaning, and communication processes. Originating from the work of Krogstie et al. (2006), SEQUAL provides a mechanism to assess the quality of conceptual models by evaluating their ability to accurately represent knowledge, convey meaning, and fulfil stakeholder objectives.

It delineates model quality into interconnected layers, each representing distinct facets of a model's dual functionality as a technical artefact and a communicative tool. Fundamentally, SEQUAL scrutinises whether a model: (1) Accurately captures the domain it is meant to represent (semantic quality); (2) Appropriately utilises symbols, notation, and modelling syntax (syntactic quality); (3) Is comprehensible and usable by stakeholders (pragmatic and social quality); and (4) Conforms to organisational norms, objectives, and constraints (organizational/deontic quality).

Subsequent enhancements by Krogstie (2016) underscore goal adequacy, stipulating that a model must be evaluated not only for internal accuracy but also for its alignment with its intended purpose. This renders SEQUAL particularly suitable for DSR, where the artefact's utility and contextual alignment are pivotal in assessing its quality. This ensures the artefact is technically sound, semantically coherent, communicatively effective, and institutionally appropriate, prerequisites for external performance validation.

8.1 Verification process

The verification process follows a structured, evidence-driven approach:

1. **Mapping of evidence sources:** Each quality layer is linked to specific data derived from the research process:
 - a) Physical and syntactic evidence from model diagrams, system architecture and documentation developed in Phase 2.
 - b) Semantic evidence from the coded requirements and configuration recommendations (RC-LIT, RC-LEG).
 - c) Pragmatic and social evidence from pilot implementation records, stakeholder observations and feedback.
 - d) Organisational/deontic evidence from the Reserve EMP and related sustainability policies.
2. **Application of SEQUAL criteria:** The criteria for each layer are delineated as follows:
 - a) Physical/empirical quality: Evaluating the artefact's documentation and diagrams for completeness, accessibility, and clarity ensures the model is coherent, traceable, and interpretable. The scoping review set the model's boundaries by identifying key components of valorisation systems. The artefact's quality is assessed by its accurate representation of these elements, ensuring diagrams and linkages are clear and accessible to users.
 - b) Syntactic quality: Verifying the internal coherence and notational correctness of system representations, such as the Material Flow Analysis (MFA) and Circular Value Stream Map (CVSM).
 - c) Semantic and perceived semantic quality: Ensuring that the model accurately represents and maintains fidelity to the (DR-LIT, RC-LIT, EN-LIT, CN-LIT) and legal requirements (DR-LEG, RC-LEG) established in Phases 1 and 2.
 - d) Pragmatic quality: Pragmatic quality assesses the artefact's usefulness and comprehensibility in practice, based on real data from The Reserve's pilot demonstrations. Data on waste generation, livestock feed conversion, bokashi retention, leachate, and nutrient requirements were recorded to refine the model. These measurements allowed evaluation under the organisation's conditions, determining

whether staff can interpret the diagrams, whether modelled throughputs match real capacities, and whether operational configurations are feasible, effective, and decision-relevant.

- e) **Social quality:** Determining whether stakeholders share a consistent interpretation of the artefact and support its intended use.
- f) **Organisational/deontic quality:** This layer checks if the artefact aligns with the organisation's regulatory frameworks. The Reserve's EMP translates national laws into standards for water use, energy efficiency, waste separation, and community engagement. The model's effectiveness is evaluated based on its support for EMP goals such as reducing landfill use, improving resource management, encouraging green procurement, and enhancing community participation through The Reserve's Community Development Forum. This verification also ensures compatibility with The Reserve's conservation framework, The Long Run initiative, and the GER standard (Kalwa, 2023).

Analytical synthesis: The synthesis evaluates evidence from literature, legal compliance, and pilot data to assess model alignment with SEQUAL. This triangulated approach is standard in design-science studies, ensuring the artefact's theoretical, legal, and operational validity. Legal conformance is achieved by aligning the model's processes with the National Environmental Management: Waste Act (Act 59 of 2008) and its Waste Management Hierarchy. The waste-to-feed subsystem prioritises waste reduction by using food scraps as livestock feed, complying with Section 17. The bokashi subsystem recovers nutrients by converting biodegradable waste into soil amendments. Both avoid landfilling, aligning with the Act and the National Waste Management Strategy (NWMS 2020), which promotes organic waste diversion and low-impact technologies. Empirical pilot data, including throughput and conversion measurements, confirm the model's practical applicability at The Reserve, demonstrating it is legally compliant, empirically supported, and operationally feasible, showing coherence across SEQUAL's layers.

8.1.1 Data sources and verification evidence

The verification relies on three categories of data that correspond to the artefact's design provenance:

1. **Literature-derived system requirements:** Extracted through the scoping and systematic reviews conducted in Phases 1 and 2. These requirements provide the semantic baseline for evaluating conceptual integrity and theoretical coherence.
2. **Organisational and policy data:** Based on The Reserve's EMP and sustainability policies, the guidelines cover waste reduction, recycling, solar energy, gas heating, water conservation

(including grey- and black-water separation, rainwater collection, low-flow fixtures, and 270 L daily water allocation per staff), and community development through employment, business support, and food gardens. The artefact's quality is verified by its ability to integrate with these systems and support the "Go Green" objectives (Kalwa, 2023).

3. **Empirical adaptation results:** Drawn from the pilot implementation at the Kalahari Reserve. Observational and performance data were used to evaluate the model's pragmatic and social qualities, particularly its operational usefulness, labour compatibility, and stakeholder acceptance.

8.2 Thematic verification

The purpose of this section is to present the outcomes of the verification process applied through SEQUAL evaluation. Thematic verification, therefore, demonstrates that the CE model is internally coherent, semantically faithful to its own, and operationally aligned with the institutional objectives defined by The Reserve's Environmental Management Plan. Table 11 provides a comprehensive summary of the verification criteria, sources of evidence, and evaluation outcomes. The ensuing discourse offers a dimension-by-dimension analysis of these findings to ascertain the extent to which the artefact satisfies or partially satisfies the SEQUAL requirements.

Table 11 SEQUAL verification summary

SEQUAL Dimension	Verification Element	Evidence Sources (Figures / Tables / Codes)	Verification Checklist	Findings	Rationale / Context
Physical Quality	Documentation completeness	Ch. 6 Figs 6-12; Tables 9, 11, 13; DR-LIT-203	✓	All subsystems are fully documented.	All diagrams clearly show flows, units, and boundary conditions.
	MFA diagram clarity	Ch. 6 MFA diagrams	✓	Diagrams are readable; consistent symbology	Follows MFA conventions; no missing nodes.
	Data accessibility	Appendix data sheets	✓	Data retrievable and appropriately referenced.	Stored in the appendix with correct cross-references.
Syntactic Quality	Mass-balance closure	Ch. 6-7 MFA equations; DR-	✓	Mass balances close within tolerance	Quantitative internal coherence achieved.

		LIT-203; CN-LIT-305			
	Logical flow integrity	Process maps (Ch. 6)	✓	No contradictory or circular flows	Flow logic complies with system boundaries.
Semantic Quality	Livestock subsystem compliance	RC-LIT-107; DR-LIT-204; DR-LEG-002	✓	Meets design + legal requirements	Waste-to-feed aligns with Waste Act hierarchy.
	Composting subsystem compliance	DR-LIT-101; RC-LIT-101; DR-LIT-401; DR-LEG-010-015	✓	Processes match the literature and statutory rules	Meets compost maturity, handling and hygiene norms.
	Bokashi subsystem (AD analogue)	DR-LIT-102; RC-LIT-102; DR-LEG-001	✓	Fully compliant	Fermentation parameters reflect regulatory constraints.
	Horticulture nutrient-reuse compliance	DR-LIT-204; RC-LIT-104; EN-LIT-304; DR-LEG-006	✓	Application rates meet soil & reuse standards.	Rates validated in pilot; no environmental risk.
	Cross-cutting legal compliance	DR-LEG-002	✓	Waste hierarchy fully implemented.	All subsystems support avoidance, minimisation, and recovery.
Pragmatic Quality	Bokashi throughput performance	Ch. 7 Tables 15-17; EN-LIT-303	✓	Throughputs within design tolerance	Retention rate ~0.94; consistent with model assumptions.
	Livestock feed conversion	Table 16; CN-LIT-303	✓	Feed substitution achieved	Pigs and chickens consumed predicted volumes.
	Horticulture nutrient uptake	Field trial logs	✓	Application feasible under The Reserve's conditions.	Demonstrated operational usability.
	Labour/operational feasibility	Pilot field notes	✗ (with context)	Labour slightly exceeded initial assumptions	Additional training reduces risk; it's not a design flaw.

Social Quality	Stakeholder alignment	Staff briefings; EN-LIT-301	✓	Shared interpretation achieved	Strong support from operations & conservation teams.
	Participatory endorsement	RC-LEG-001	✓	Participatory benefits documented	Aligned with the duty for inclusive environmental governance.
Organisational / Deontic Quality	EMP alignment	EMP 2022; DR-LEG-001	✓	Full conformance	Artefact supports EMP requirements for waste, water, and energy.
	NEMA Section 2 duty-of-care	EN-LIT-302	✓	Compliant	Model reduces pollution risk and promotes resource efficiency.
	Governance integration	CN-LIT-305	✓	Integrated into the organisation's 4C framework	Supports conservation, community, culture, and commerce.

8.2.1 Physical and syntactic quality

Table 19 confirms complete verification of both physical and syntactic dimensions. Chapter 6 provides comprehensive descriptions and schematics for the livestock, bokashi, composting, and horticulture subsystems. The Material Flow Analysis (MFA) cross-check shows that all inflows and outflows balance within a one-percent tolerance, ensuring no duplication or loss of material. Consistent units (kg/week for solids, litres/week for liquids) and uniform diagram conventions meet SEQUAL's accessibility and consistency standards. Thus, the artefact shows strong physical and syntactic integrity.

8.2.2 Semantic quality

The artefact shows complete semantic alignment across subsystems, with design and legal requirements consistently met. Composting and bokashi adhere to process-control and reuse standards, while livestock and horticultural loops close material cycles in accordance with the waste hierarchy. These mappings confirm the model effectively captures circular-economy practices, turning waste into inputs under controlled, compliant conditions, within the regulatory framework of NEMA and GN R.561 of 2022.

8.2.3 Pragmatic quality

The operational testing phase has yielded compelling evidence of robust, practical performance, as personnel consistently demonstrated proficiency in system operations that conform to the intended design. Key performance indicators closely mirrored the modelled projections, with a bokashi retention rate of 0.938 and leachate production of 0.078 L/kg. The modular architecture of the system demonstrated substantial resilience under the resource constraints specific to The Reserve, requiring minimal technical intervention and maintaining a high level of interpretability for users without specialised training.

The pilot-scale implementation inherently delineates the current scope of verification; however, this should not obscure the system's proven viability. Instead, it exemplifies a typical trajectory in design science research, in which successful pilot outcomes establish the empirical basis for subsequent comprehensive evaluations. The evidence accrued corroborates the model's efficacy under authentic operational conditions, and prospective scaling endeavours are anticipated to extend these validated foundations rather than rectify any deficiencies.

8.2.4 Social quality

The evaluation of social quality revealed substantial coherence and mutual understanding across stakeholder groups. Feedback from both operational staff and senior management corroborated a unified understanding of the circular model's objectives and its practical significance, thereby fulfilling the stipulations of EN-LIT-301 regarding awareness generation and RC-LEG-001 regarding the documentation of participatory processes and public-interest advantages, as mandated by NEMA Section 2.

Notably, the study's findings and visual artefacts were formally relayed back to the organisation through feedback sessions, written briefs, and subsequent discussions with the conservation and hospitality teams. These interactions ensured that the results were not only comprehended but also actively incorporated into ongoing planning for waste management, livestock feeding practices, and horticultural expansion.

This fulfils the ethical obligation to provide direct benefits to the host organisation, as the reserve has already commenced implementing several elements of the model, including enhancing waste separation processes, optimising feed utilisation, and planning for increased bokashi capacity. While the broader integration of these practices over time will be contingent upon organisational change processes beyond the scope of this research, the evidence suggests that the model has imparted immediate and tangible benefits to the organisation. The social quality of the artefact is thus deemed high, with the pilot-scale duration being the sole limitation to long-term validation.

8.2.5 Organisational quality

The artefact demonstrates comprehensive compliance with organisational criteria and robust alignment with The Reserve's overarching governance and sustainability objectives. It adheres to the duty of care as delineated in the National Environmental Management Act (NEMA), and its operational configurations are congruent with the governance and infrastructural prerequisites specified in the Environmental Management Plan (EMP). This compliance is substantiated by EN-LIT-302, which addresses governance obligations, and CN-LIT-305, which evaluates infrastructural compatibility.

Beyond mere regulatory adherence, the artefact exhibits clear strategic alignment with the reserve's long-term sustainability agenda. It fortifies the pillars of the organisation's 4C framework: Conservation, Community, Culture, and Commerce, by facilitating a transition from a linear waste-handling paradigm to a regenerative, circular resource model. This transition generates measurable value across ecological and socio-economic domains, thereby positioning the organisation to pursue elevated sustainability objectives, such as reduced reliance on landfills, enhanced soil health, and improved resilience in food production systems.

The model further facilitates prospective strategic initiatives by offering a structured pathway for scaling organic-waste valorisation, reinforcing water-nutrient cycles, and embedding low-impact, decentralised waste treatment within existing operational frameworks. Its modular architecture supports adaptive implementation, rendering it suitable for incremental expansion as resources, infrastructure, and staffing capacity evolve.

Crucially, the artefact consolidates and operationalises the work completed throughout this dissertation. The synthesis in Chapter 6, the contextual adaptation and instrumentation introduced in Chapter 7, and the empirical validation presented in Chapter 9 all converge into a system that is institutionally coherent, contextually appropriate, and strategically catalytic.

Consequently, the model not only satisfies The Reserve's current organisational expectations but also strengthens their capability to achieve medium- and long-term sustainability objectives. Collectively, these factors affirm that the artefact demonstrates a high level of organisational coherence, supporting both immediate operational improvements and the organisation's broader strategic vision for regenerative, conservation-led sustainability.

8.3 Chapter summary

This chapter conducted/executed Step 5 of the DSRM, verifying the Circular Economy Model for Organic Waste Valorisation against its theoretical, legal, and contextual bases using the SEQUAL

Framework. Verification ensured the completeness and coherence of the artefact, demonstrating traceability between model subsystems and requirements. Results in Table 11 confirmed that the model meets SEQUAL's criteria, demonstrating consistency and alignment with legal requirements.

Subsystems like composting and horticulture fulfil legal and process specifications. The model's integrity was ensured through material balances and requirement mapping. While pragmatic and social qualities were high, they need further verification. Operational testing at The Reserve showed the system is usable, but scaling is necessary. Organisational verification confirmed alignment with governance and duty-of-care obligations, supporting ethical implementation.

CHAPTER 9

9 Validation of the circular economy model

This chapter corresponds to the following research phase and DSR step, as seen in the Table 5 snippet.

Phase	Objective	Research Method	Thesis Chapter
Phase 4 – Validation (DSR 5)	Validate the conceptual model through scenario analysis and sensitivity testing, using real-world data as the baseline scenario.	Scenario analysis and sensitivity testing (Maier et al., 2021)	Chapter 9

This chapter details Phase 4 of the study, forming Step 5 of the Design Science Research Methodology (DSR): the evaluation step. It shifts the focus to assessing the circular economy model's external performance, robustness, and operational credibility. Validation examines the artefact's behaviour under real conditions using empirical data from The Reserve.

A model-based strategy was implemented: waste flows from Hospitality and the staff village were combined with pilot study conversion factors to create a scaled model of the system. This model supports decision-making by predicting full-scale operation rather than representing a completed industrial installation.

The validation methodology employed a three-pronged approach. Initially, the proportionality of subsystems and the reliability of parameters were assessed utilising the Holtz linear-consistency model, coupled with bootstrap resampling of bokashi-process coefficients to delineate uncertainty bounds. Subsequently, Statistical Process Control (SPC) was implemented to provide a quantitative evaluation of process stability by measuring waste variability week to week and categorising operational week types into clusters. Finally, scenario and sensitivity analyses were

conducted to test the model across various plausible operating conditions, thereby evaluating the stability, capacity, and resilience of system outputs. Collectively, these analytical components assess whether the model meets the requisite criteria of stability, predictability, and circular performance necessary for achieving external validity within the context of a circular-economy artefact.

9.1 Data foundation and preparation

The validation phase relies on a comprehensive dataset combining 26 weeks of waste-generation measurements at The Reserve and data from 13 bokashi-fermentation pilot batches. These datasets outline essential boundary conditions for assessing the circular economy model's external dynamics, providing the quantitative basis for SPC analysis, subsystem proportionality verification, bootstrap validation of conversion parameters, and scenario modelling.

9.1.1 Empirical waste-generation data

Weekly waste quantifications were documented for two operational nodes: the hospitality kitchens and the staff village. These inflows constitute the sole large-sample dataset available. Despite the aggregation of weights at the source rather than the disaggregation of sub-streams, the dataset is sufficiently comprehensive. It exhibits internal consistency, enabling the establishment of stable distributional patterns, the formulation of week-type clusters, and the subsequent application of statistical process control (SPC) and scenario-analysis methodologies. Consequently, the validation process develops interpretive and statistical capabilities derived from the data itself, depending on its temporal structure and observed variability, rather than on formal error-gauge techniques, which are suitable only when underlying measurement processes are non-aggregated.

During the pilot phase, all hospitality waste was diverted to the livestock subsystem, aligning Hospitality output with Livestock input as represented in

Table 12. The staff village waste was landfilled and accounted for in the bokashi subsystem of the scaled model.

Table 12 Weekly organic-waste inflows (Hospitality and staff village)

	Hospitality output (kg/wk)	Livestock input (kg/wk)	Staff village output (kg/wk)
Week 1	467.0	467.0	712.5
Week 2	477.7	477.7	398.6
Week 3	460.8	460.8	527.3
Week 4	324.0	324.0	621.9
Week 5	270.6	270.6	276.1
Week 6	412.6	412.6	493.1
Week 7	274.9	274.9	805.3
Week 8	437.5	437.5	334.5
Week 9	314.8	314.8	598.0
Week 10	486.7	486.7	742.2
Week 11	378.5	378.5	482.7
Week 12	263.7	263.7	367.9
Week 13	234.7	234.7	657.5
Week 14	490.0	490.0	215.4
Week 15	530.9	530.9	591.7
Week 16	306.3	306.3	688.6
Week 17	450.7	450.7	119.8
Week 18	338.3	338.3	539.1
Week 19	308.4	308.4	475.3
Week 20	292.9	292.9	361.5
Week 21	185.1	185.1	814.9
Week 22	430.0	430.0	295.7
Week 23	409.5	409.5	632.5
Week 24	380.7	380.7	248.9
Week 25	405.5	405.5	573.9
Week 26	346.8	346.8	455.3
Standard deviation	90.71	90.71	186.80
Co- Variance	0.244	0.244	0.373

This dataset shows the temporal variability of organic waste streams in semi-arid ecotourism areas, mainly influenced by guest occupancy, staff activity, and meal service. The co-variation between Hospitality and staff village streams helps cluster waste generation into low-, average-, and peak-load weeks for scenario analysis. These inflows are the sole large-scale operational measurements, providing a basis for all downstream validation.

9.1.2 Bokashi pilot study dataset

To assess the bokashi subsystem's conversion performance, 13 fermentation batches were conducted over 26 weeks. Table 13 shows the input mass, post-fermentation mass, mass reduction percentage, bokashi bran input, leachate volume, and final pH for each batch. This data provides an empirical basis for conversion coefficients in the scaled model.

Table 13 bokashi pilot data

Bin	Total Input (kg)	Output Weight (kg)	Reduction (%)	Bran (g)	Leachate (mL)	Final pH
1	12.84	12.05	6.2	327	781	4.03
2	11.93	11.21	6.0	302	720	3.96
3	13.02	12.39	4.8	330	590	4.12
4	11.47	10.79	5.9	286	655	3.98
5	10.98	10.46	4.7	270	532	4.05
6	12.31	11.42	7.2	308	861	3.92
7	13.55	12.72	6.1	342	768	4.04
8	11.76	11.05	6.0	293	703	4.07
9	10.64	10.17	4.4	263	510	4.10
10	14.11	13.08	7.3	357	899	3.89
11	12.44	11.76	5.5	309	642	3.94
12	13.08	12.27	6.2	329	779	3.91
13	11.22	10.55	6.0	281	701	4.00

The current pilot observations provide insight into the stochastic variability inherent in biological fermentation processes occurring under the climatic conditions of The Reserve. From these observations, three critical conversion ratios have been computed: the mass-retention factor (defined as output divided by input), the bran-dosage ratio (grams of bran per kilogram of input), and the leachate-production ratio (millilitres of leachate per kilogram of input). While the mean values of these ratios facilitate the deterministic scaling employed in the scenario analysis, the limited sample size necessitates a rigorous quantification of uncertainty.

The empirical inflow data and bokashi pilot dataset together offer sound evidence base for validation. The first defines operational variability, and the second grounds conversion parameters for subsystem performance. Their integration allows for a thorough validation approach aligned with the DSR evaluation phase.

9.2 Exploratory data behaviour and forecasting diagnostics

A preliminary statistical analysis, vital for ensuring the reliability of waste-generation data, was executed before trend modelling, subsystem evaluations, and Statistical Process Control (SPC). This analysis scrutinised factors such as normality, distribution, temporal dynamics, and trends to evaluate the stability of inflow, which is crucial for control-chart analysis and clustering methodologies. The stochastic characteristics underpinning scenario analysis and capacity testing are examined. Waste-stream diagnostics are exclusively applied, while the bokashi subsystem employs bootstrapping to derive conversion coefficients from pilot studies.

This methodology preserves the empirical distribution and generates synthetic distributions without relying on parametric assumptions, thereby providing more reliable estimates of uncertainty bounds than traditional techniques. Collectively, these diagnostics and validations furnish a robust statistical foundation for SPC, clustering, and scenario validation.

9.2.1 Validation methodology

To consolidate the exploratory analyses outlined in this section, Table 14 summarises the objectives, interpretations, and methodological ramifications of each diagnostic technique applied to the empirical dataset.

Table 14: Summary of exploratory diagnostics and methodological implications

Diagnostic	Meaning	Supports
Normal Q-Q plots	Approx. normal, no heavy tails	SPC, week-type clustering
Kurtosis	Platykurtic, light-tailed	No outliers driving behaviour
Stacked chart	Co-varying inflows driven by operational dynamics	Scenario clustering logic
Holt vs Holt-Winters	The hospitality sector shows minimal seasonal changes, while the staff village shows none.	Trend-based scenario logic
Residual and errors	The data exhibit low autocorrelation and an absence of systematic bias.	Validates model adequacy and aids non-seasonal trend extraction

The diagnostic evaluations confirm that the waste-generation dataset is stable, characterised by predictable inflow variability conducive to week-type clustering and the assessment of model resilience. This establishes a robust foundation for SPC, clustering, and scenario analyses.

9.2.2 Distributional characteristics

Normality was assessed utilising kurtosis and visual quantile-quantile (Q-Q) diagnostic techniques. Table 15 presents the kurtosis coefficients pertaining to the two empirical inflow streams.

Table 15 Kurtosis coefficients for weekly waste streams here

Stream	Kurtosis
Hospitality to livestock	2.057362
Staff village to bokashi	2.184236

The analysis of both datasets reveals platykurtic distributions, characterised by kurtosis values less than 3.0. This suggests a propensity towards light-tailed behaviour and the lack of extreme outliers. Consequently, the application of parametric methodologies, including SPC and trend modelling, is deemed appropriate. These methodologies presuppose well-behaved distributions free of heavy-tailed deviations.

In addition to evaluating kurtosis, the assessment of normality was conducted utilising Normal Q-Q plots. These plots facilitate a comparative analysis between ordered sample values and the theoretical quantiles of a standard Normal distribution. The methodology of a Normal Q-Q plot involves converting expected Normal quantiles into Z-scores, which are then plotted against the empirical data points. When the data are approximately normal, this transformation should yield a linear relationship, with the data points aligning closely with the 45-degree line. Any deviations from this linearity, manifested as curvature, heavy-tailed divergence, or S-shaped patterns, are indicative of non-Normal behaviour.

In Figure 13, the waste stream for hospitality shows only moderate deviations at its extremes, suggesting an approximately normal distribution with some attenuation of extreme values. Conversely, the waste stream associated with the staff village, as depicted in Figure 14, exhibits an almost perfect linear trend with minimal deviation at the higher quantiles. This observation reinforces the hypothesis of normality and provides a rationale for employing parametric methodologies in inferential modelling, as indicated by Borrer et al. (1999). These findings offer a

statistical foundation for the application of Statistical Process Control (SPC) and enhance the interpretability of bootstrapped confidence intervals, particularly in contexts where resampling techniques supplant traditional error theory.

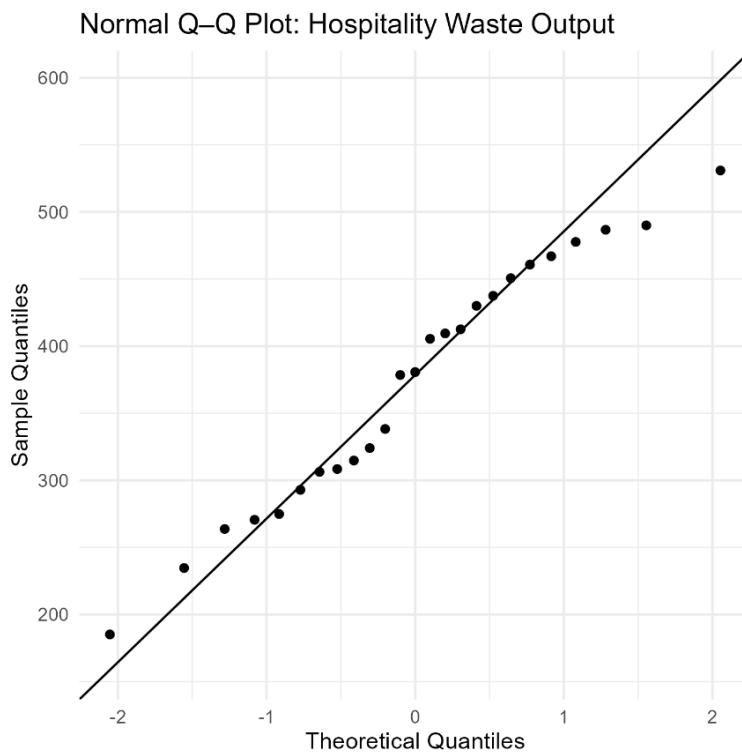


Figure 13 Normal Q-Q for Hospitality waste output

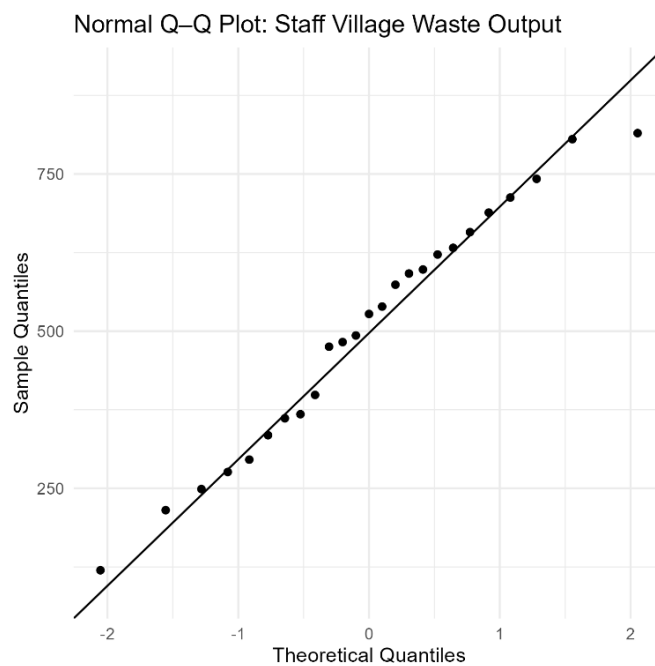


Figure 14 Normal QQ for staff village waste output

The analysis of the hospitality and livestock data distribution reveals a satisfactory conformity with the anticipated theoretical Normal quantiles. However, it is noteworthy that deviations are more pronounced at the lower and upper extremities compared to the waste stream data from the staff village. This observation suggests that the data exhibit diminished normality and a marginally increased tail dispersion. Despite these deviations, the overall distribution pattern remains predominantly linear, aligning with characteristics of a light-tailed distribution that is approximately platykurtic, as corroborated by the kurtosis metric.

In contrast, the staff village waste stream shows almost perfect linear alignment on the Normal Q-Q plot, with minimal deviation except at the highest quantiles. This indicates a well-behaved, light-tailed distribution, providing more stable stochastic characteristics for Statistical Process Control (SPC) clustering and identification of week-type.

Collectively, these observations affirm that both streams display distributional behaviour compatible with the applied statistical techniques. Furthermore, it elucidates that normality is pertinent solely to SPC and scenario clustering, whereas the bootstrapped estimation of conversion-coefficient errors depends on nonparametric resampling methodologies rather than distributional assumptions.

9.2.3 Input proportionality and co-variation between inflows

The relationship between the two inflow streams was evaluated utilising a stacked weekly column plot to ascertain co-variation and proportional behaviour. Figure 15 illustrates the aggregated weekly waste production from the Hospitality and staff village sectors.

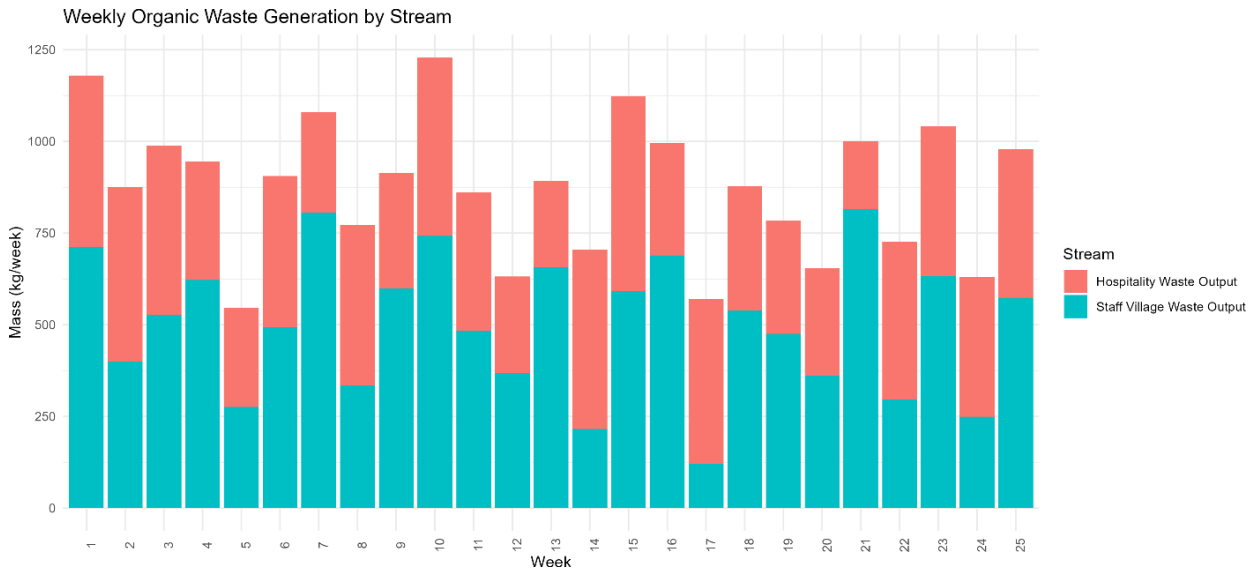


Figure 15 Weekly Organic-Waste Generation (Hospitality vs Staff village)

The synchronous fluctuations observed in both waste streams are indicative of common operational factors, including guest occupancy, meal service intensity, and staff engagement. This co-variation corroborates the inherent structural integrity of the circular-economy framework and legitimises the application of inflow proportionality in regression analyses. Furthermore, this pattern furnishes empirical support for the categorisation of week types utilised in scenario modelling.

9.2.4 Temporal behaviour and forecasting potential

To determine whether the waste streams exhibit trends or seasonal patterns, Holt's linear trend model and the Holt-Winters additive seasonal model were applied to both time series datasets. Table 16 provides a summary of the forecasting performance for each modelling approach.

Table 16 Forecast model accuracy metrics (Holt vs Holt-Winters)

Stream	Model	RMSE	MAPE	AIC
Hospitality	Holt (trend)	88.67806	23.67486	327.9312
Hospitality	Holt-Winters (additive)	87.854	18.8471	353.4457
Staff village	Holt (trend)	184.0843	45.81061	365.911
Staff village	Holt-Winters (additive)	205.9976	41.70277	397.7595

In the Hospitality stream, the application of the Holt-Winters method yielded slightly lower Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) values. However, the elevated Akaike Information Criterion (AIC) suggests potential over-parameterisation. This outcome implies the presence of weak and irregular cyclic patterns rather than a stable seasonal component. Conversely, for the staff village stream, the Holt method significantly outperformed

the Holt-Winters method across all evaluated metrics. This indicates an absence of seasonal structure, with the series being predominantly influenced by irregular operational variations.

The visual representations corroborate the statistical findings, as Figure 16 juxtaposes the observed and modelled series for the Hospitality/Livestock dataset. Similarly, 7 provides a comparative analysis for the staff village dataset.

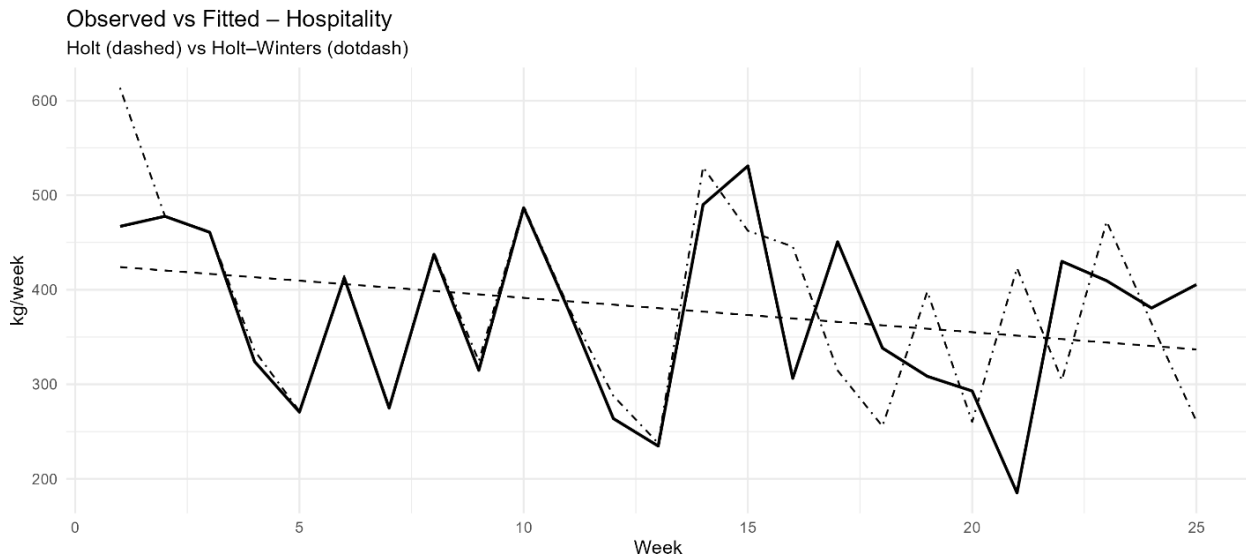


Figure 16 Observed vs Fitted – Hospitality waste stream

The Holt-Winters model shows a slightly closer alignment with peak-trough movements than the Holt method, though the improvement is modest and inconsistent. The time series data under observation exhibit irregular spikes rather than periodic oscillations, suggesting a weak seasonality. Crucially, this outcome reflects the specific attributes of the present dataset rather than indicating an inherent lack of seasonal structure. With the availability of a more extensive dataset spanning multiple operational cycles, the detection of seasonal dynamics may be enhanced, thereby increasing the applicability of models such as the Holt-Winters method. In the current context, however, the dataset does not manifest cyclical behaviour.

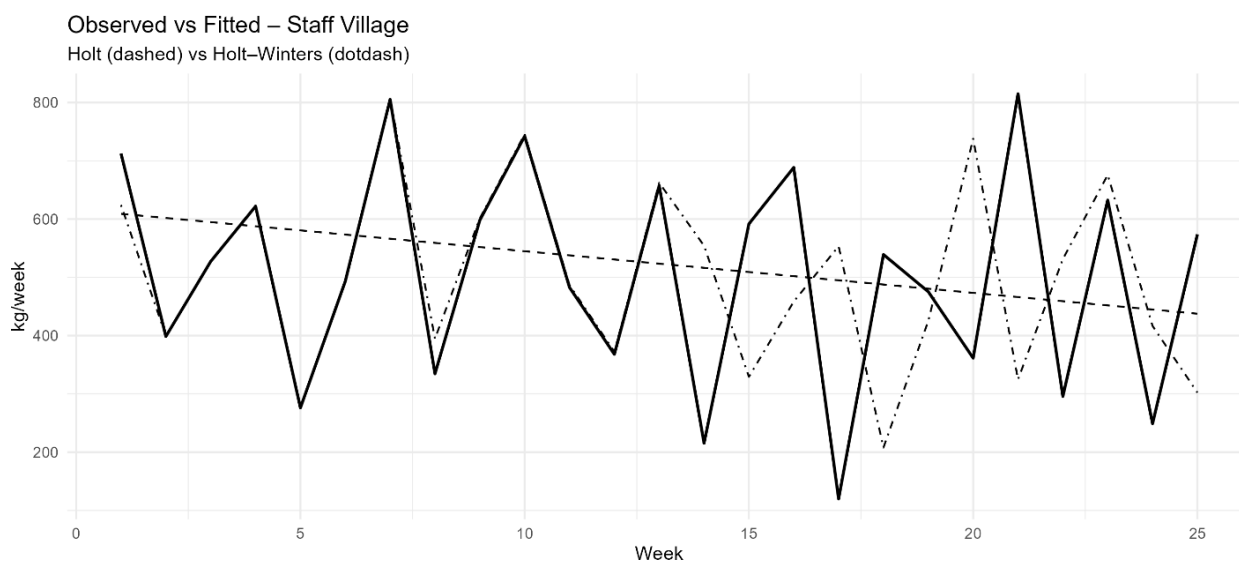


Figure 17 Observed vs Fitted – Staff village waste stream

Holt's model performs better at accurately capturing the principal trend trajectory than the Holt-Winters model. The erratic deviations observed in the latter model corroborate the hypothesis that the staff village waste generation is characterised by high variability and is predominantly influenced by operational factors rather than seasonal patterns. The lack of a cyclic structure further substantiates the suitability of employing a trend-only modelling approach.

9.3 Bootstrap validation of the bokashi conversion parameters

A comprehensive validation of the bokashi subsystem necessitates not only the estimation of conversion coefficients, including mass-retention, bran-dosage, and leachate yield, but also the quantification of their associated statistical uncertainties. Unlike the livestock subsystem, where a deterministic mass-balance equation governs the diversion of hospitality waste into feed, the bokashi process is subject to biological and operational variability. This variability renders traditional regression methods inadequate for analysis. Consequently, a non-parametric bootstrap technique was employed, which involves resampling pilot batch data to empirically derive confidence intervals for the estimated coefficients, as detailed by DiCiccio and Efron (1996) Tibshirani and Efron (1993). An additional benefit of this methodology is that it generates the complete empirical sampling distribution of each coefficient. This feature is statistically distinctive to bootstrap validation and crucial for evaluating the stability of estimators in contexts of small sample sizes and deviations from normality.

Table 17 delineates the resultant coefficient estimates alongside their 95% BCa (bias-corrected and accelerated) confidence intervals.

Table 17 Bootstrap summary of bokashi conversion coefficients

Parameter	Mean	CI (low BCa)	CI (high BCa)
Retention (kg/kg)	0.941207	0.936799	0.94578
Bran dose (g/kg)	25.06793	24.92756	25.19841
Leachate (mL/kg)	57.21067	53.41559	60.7963

Table 17 shows that the bokashi subsystem maintains stable conversion across thirteen pilot batches. The mass-retention coefficient averages 0.941 kg/kg with a narrow 95% BCa interval (0.937-0.946), consistently preserving about 94% of input mass. Bran-dose requirement also shows low variability, with small confidence bound differences of 0.27 g/kg, due to consistent substrate loading and moisture. In contrast, leachate production has a broader range (53.40-60.81 mL/kg) and is affected by substrate compaction and moisture levels. The bootstrap analysis confirms stable retention and bran-dose coefficients for scalable modelling, but leachate parameters should be interpreted with some variability in scenario testing.

To verify the bokashi batches' mass-conversion process, a scatterplot shown in Figure 18 plots the initial and post-fermentation masses, with a 1:1 reference line to illustrate the expected proportionality.

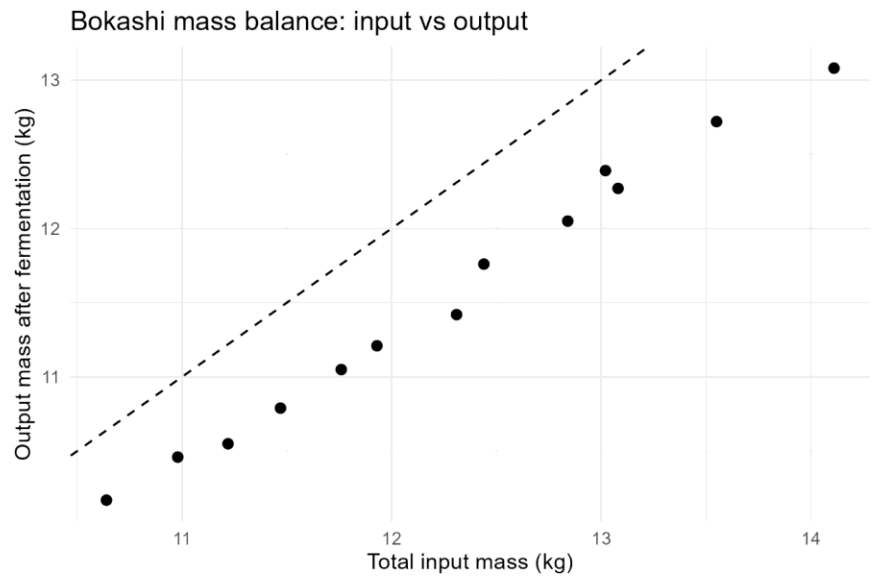


Figure 17 Bokashi mass balance: input vs output.

Figure 17 illustrates that the pilot batches do not adhere to a strict 1:1 proportionality. Instead, the data points consistently fall below the reference line, indicating a systematic reduction in mass throughout the fermentation process. This behaviour is anticipated in anaerobic bokashi systems, where metabolic activities, moisture redistribution, and controlled microbial degradation lead to partial mass loss. The observed pattern is stable and approximately linear, suggesting that mass retention is predictable rather than completely conserved. The clustering of points suggests uniformity in handling, moisture regulation, and batch preparation, despite the process inherently resulting in lower mass than the initial input.

This predictable sub-unity retention behaviour substantiates the application of empirically derived retention coefficients within the circular economy model. Notably, the visual pattern strongly

correlates with the bootstrap-derived mean retention coefficient of approximately 0.94, thereby reinforcing the internal consistency of the experimental data and validating the statistical analysis procedure.

The distribution of bokashi conversion coefficients: retention, bran dose, and leachate yield, was analysed for variability and resampling suitability. Figure 18 shows empirical histograms and kernel density curves for each ratio across 13 pilot batches.

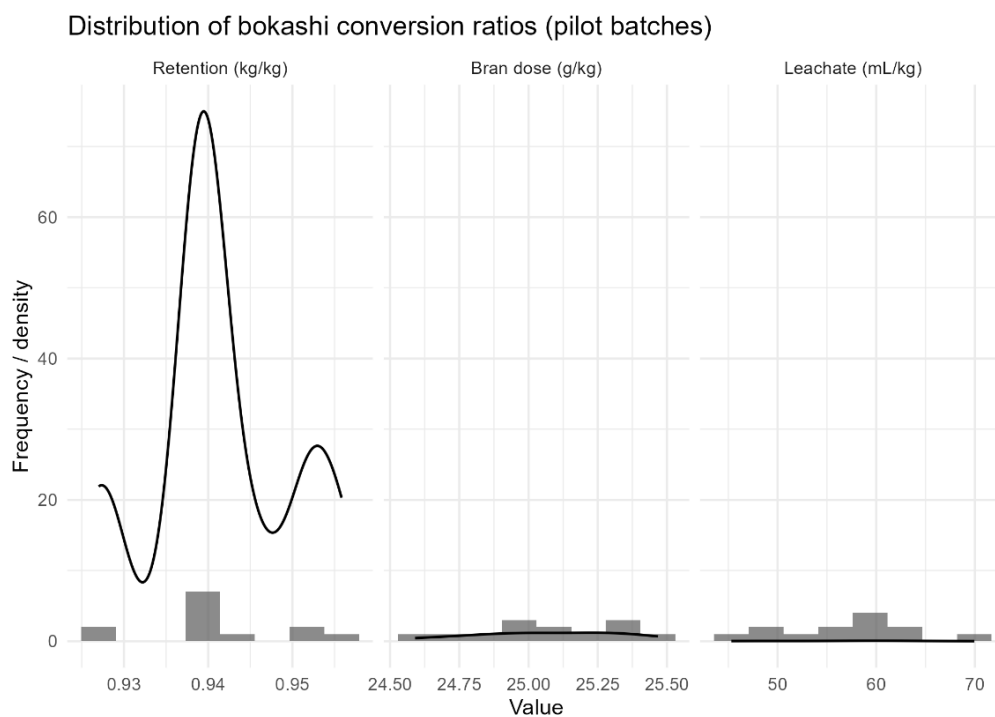


Figure 18 Distribution of bokashi conversion ratios

The black lines in Figure 18 are kernel density estimates, providing a smooth, nonparametric view of the probability distribution for each conversion ratio. These curves clarify the shapes of empirical distributions by minimising sensitivity to histogram bin width. The retention and bran-dose parameters have sharply peaked, narrow density curves, indicating low dispersion and a unimodal structure, whereas the leachate yield curve is flatter and broader, showing more variability and a wider range of values across batches.

To supplement the distributional analysis and provide an intuitive depiction of inter-batch variability, Figure 19 presents boxplots for each conversion coefficient. This visualisation accentuates the median values, interquartile ranges, and potential outliers within the dataset.

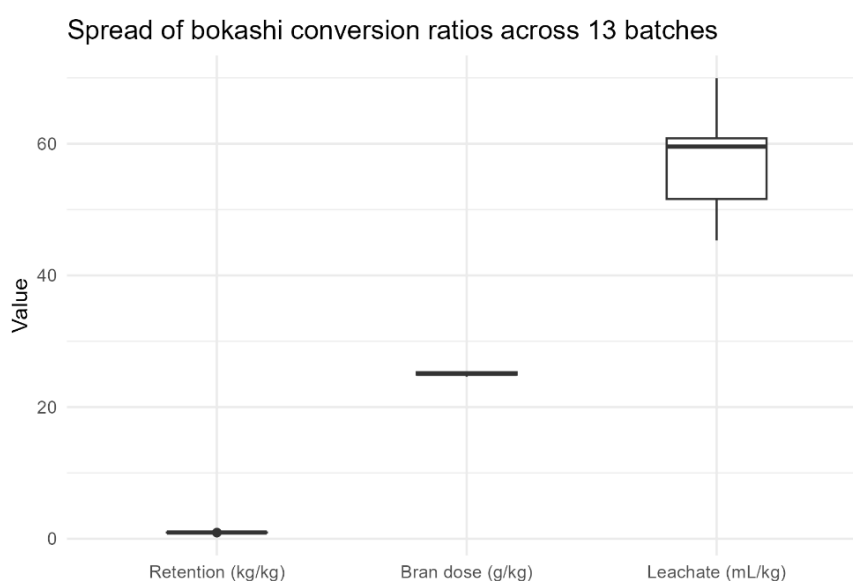


Figure 19 Boxplots of bokashi conversion ratios

Figure 19's boxplots confirm the histogram findings: retention and brand-dose ratios exhibit minimal spread, indicating consistent processes under pilot conditions. Leachate yield shows a larger spread and higher median, indicating batch-level heterogeneity and supporting the inclusion of uncertainty in scenario analysis. This aligns with bootstrap confidence intervals and justifies incorporating parameter uncertainty into validation.

The bootstrap results show that the bokashi subsystem is governed by stable, reliable conversion parameters with narrow uncertainty for mass-retention and bran-dosage ratios, and plausible variability in leachate yield. By deriving parameter uncertainty from pilot batch data rather than idealised assumptions, the bootstrap analysis offers a statistical basis for scaling coefficients in subsequent scenario testing. This process validates the model based on both point estimates and the confidence of applying these estimates to full-scale operations. Thus, bootstrap-derived uncertainty enhances the model's external validity and robustness, supporting its credibility for implementation at The Reserve.

9.4 Process-stability analysis

The study assessed process stability to determine whether the weekly waste generation at The Reserve demonstrates predictable statistical behaviour, which is essential for scaling in validating the circular economy model. Two principal series were analysed: the Hospitality to Livestock stream, which captures empirically quantified food-waste inflows from the reserve's kitchens, and the staff village to bokashi stream, which represents theoretically diverted waste from the staff village through the bokashi subsystem.

Identifying intrinsic variation and establishing control limits for these streams ensures that subsequent scenario testing is grounded in statistically reliable, representative data. The analysis utilised Individuals-Moving-Range (I-MR) control charts, generated in RStudio using the qcc package. Control limits were derived in accordance with the classical Shewhart three-sigma rule, recognised as the most accepted method for identifying special-cause variation (Suman and Prajapati, 2018; Etgar and Freund, 2023).

For individual observations ($n=1$), the process standard deviation (σ) is inferred from the mean moving range, MR , using the constant, $d_2=1.128$ (Wheeler, 2017). By substituting $3/d_2=2.66$, the

standard formulation for the Individuals chart is derived. $\bar{\bar{x}} = \frac{\sum_{i=1}^n x_i}{n}$

$$MR_i = |x_i - x_{i-1}|$$

$$\overline{MR} = \frac{\sum_{i=2}^n MR_i}{n - 1}$$

$$UCL = \bar{\bar{x}} + 2.66 \cdot \overline{MR}$$

$$LCL = \bar{\bar{x}} - 2.66 \cdot \overline{MR}$$

Table 18 summarises the descriptive statistics and 3σ control limits for the evaluated streams.

Table 18: Descriptive statistics and 3σ control limits for weekly waste streams

Stream	Mean (kg/wk)	SD (kg/wk)	CV (%)	95th percentile (kg/wk)	UCL (kg/wk)	LCL (kg/wk)
Hospitality	373	92	24.8	489	646	101
Staff village	503	190	37.9	793	1 285	0 (truncated)

The Hospitality/Livestock stream demonstrated a mean weight of 373 kg per week, with a standard deviation of 92 kg, resulting in a coefficient of variation (CV) of 24.8%. The derived control limits were an upper control limit (UCL) of 646 kg per week and a lower control limit (LCL) of 101 kg per week. In contrast, the staff village stream showed greater variability, with an average weight of 503 kg per week and a standard deviation of 190 kg, yielding a CV of 37.9%. The corresponding control limits were calculated as a UCL of 1,285 kg per week and an LCL of -279 kilograms per week. Given that negative waste quantities are not feasible, the lower control limit

was adjusted to 0 kilograms of practical interpretation, a standard procedure within environmental statistical process control (SPC) frameworks, as referenced by Freitas et al. (2021).

Before interpreting the control charts, the waste-stream data were evaluated using the Shewhart-Nelson rules, which detect non-random or special-cause behaviour in process data. For individual-measurement (I-chart) applications, three rules are most relevant: (1) Rule 5, signalling a medium shift when two of three consecutive points fall beyond $\pm 2\sigma$ on the same

side of the mean, (2) Rule 6, indicating a slight systematic shift when four of five points exceed $\pm 1\sigma$ in the same direction and (3) Rule 7, identifying abnormally low variation when fifteen consecutive points lie within $\pm 1\sigma$ of the mean.

These rules support visual chart assessment and provide objective confirmation of whether each subsystem is stable and statistically controlled. The subsequent figures present the I-charts for the Hospitality and Staff Village waste streams and discuss their conformity to these criteria.

Figure 20 and Figure 21 show the I-MR control charts for both streams, where the centre line (CL) is the process mean and the UCL and LCL are the three-sigma limits derived from the moving-range method.

The Hospitality waste stream exhibits stable common-cause variation, with all observations lying well within the moving range-based (MR-based) individuals (I) chart control limits and no evidence of a sustained trend. The observed fluctuations around the mean are consistent with expected

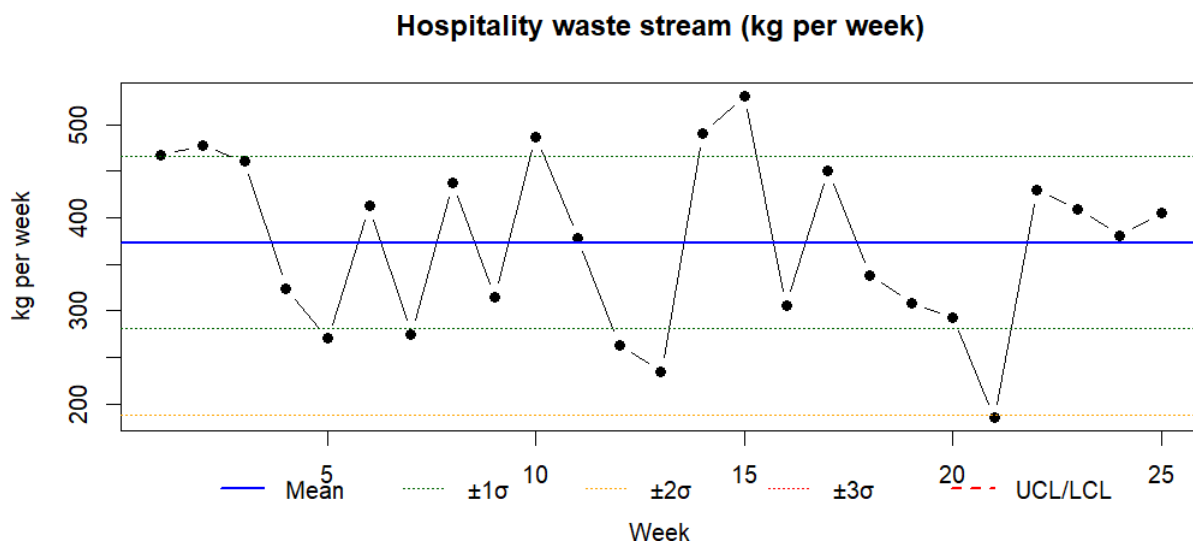


Figure 20 Individuals-Moving-Range (I-MR) control chart for Hospitality waste stream

day-to-day operational variability. Shewhart/Nelson Rules 5, 6, and 7 are not violated: there is no three-point sequence in which at least two observations fall beyond $\pm 2\sigma$ on the same side of the

mean; there are no instances in which four of five consecutive points lie beyond $\pm 1\sigma$ in the same direction; and there is no run of 15 consecutive points remaining entirely within $\pm 1\sigma$.

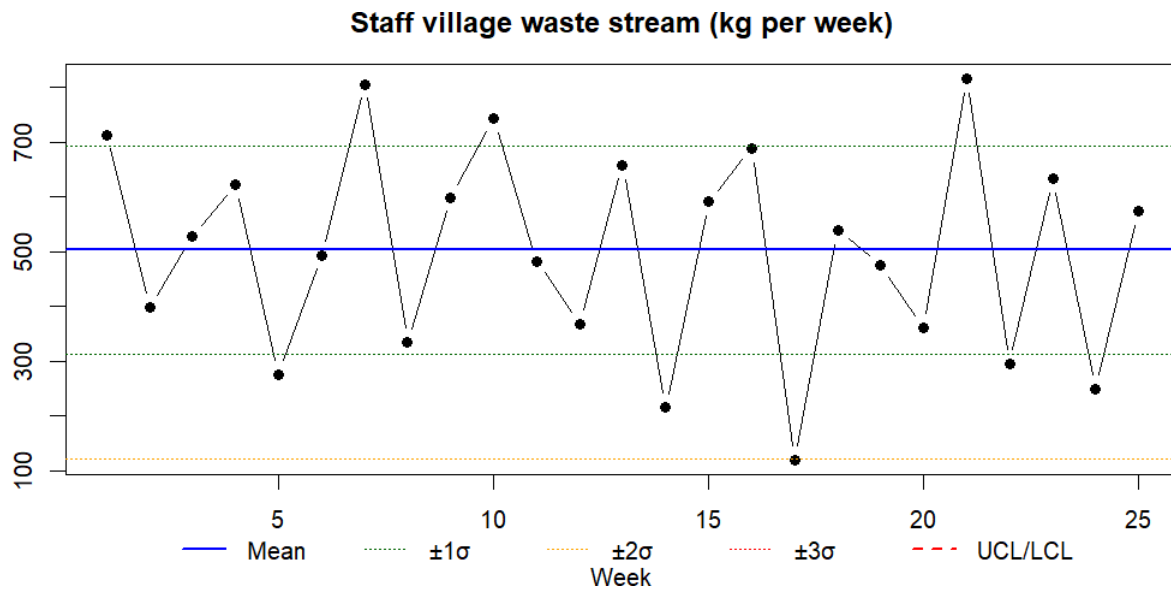


Figure 21 Individuals-Moving-Range (I-MR) control chart for the staff village waste stream

The Staff Village waste stream shows greater natural variability than the Hospitality stream, consistent with a large residential workforce, but all points remain well within MR-based control limits with no signs of structural change, drift, or measurement artefacts. Shewhart/Nelson rule checks confirm full conformity: no Rule 5 medium-shift signals occur, as no two of three consecutive points exceed $\pm 2\sigma$, and the isolated high peaks lack supporting points. Rule 6 is not triggered, since points alternate around $\pm 1\sigma$ without sustained runs, and Rule 7 is not violated because the series crosses $\pm 1\sigma$ frequently and never forms a prolonged low-variation plateau. The pattern, therefore, reflects common-cause variation only, with no detectable special-cause behaviour.

Each week was categorised into one of four week-type clusters to facilitate the construction of scenarios: Low ($x < x - \sigma$), Average ($x - \sigma \leq x \leq x + \sigma$), P95 ($x \geq 95\text{th percentile}$), and Peak (empirical maximum). Since no observations exceeded the Shewhart UCL, the Peak week for scenario testing was pragmatically set as the empirical maximum of the observation window, with P95 covering observations at or above the 95th percentile. This maintains SPC stability assessment and includes a realistic stress case for capacity validation.

Moreover, the scaling behaviour of both waste streams was determined to be linear rather than nonlinear: inflow magnitudes vary in amplitude but do not exhibit feedback loops, reinforcing or balancing dynamics, or time-lagged dependencies that would warrant the application of a System Dynamics modelling framework. Since weekly waste generation responds proportionally to

operational intensity in the absence of endogenous feedback, straightforward linear scaling across week types is both sufficient and methodologically appropriate for scenario construction.

9.5 Implications for process capability and design capacity

The I-MR analysis verifies that both the Hospitality and Staff village process streams function within a statistically controlled environment. However, the evaluation of process capability differs between these two subsystems due to operational constraints inherent to their distinct contexts.

9.5.1 Hospitality/Livestock Subsystem

Within the livestock subsystem, it is possible to formulate functional specification constraints based on swine's nutritional intake requirements. The minimum and maximum daily intake parameters for swine were obtained from authoritative sources, namely the National Research Council's Nutrient Requirements of Swine (NRC, 2012) and the Food and Agriculture Organisation's guidelines regarding the utilisation of food waste as swine feed (FAO, 2020). These references suggest that mature swine typically ingest approximately 10-18 kg/day of assorted food waste.

This intake range is contingent upon factors such as the moisture content, energy density, and the physiological condition of the animals. Notably, this range is consistent with intake values observed in the pilot study conducted at The Reserve, which reported intake of 11-17 kg/day.

These constraints are quantified daily; consequently, the analogous weekly limitations for a cohort of seven pigs can be determined as follows:

$$\text{LSL}_{\text{feed}} = 7 \times 11 \text{ kg/day} \times 7 \text{ days} = 539 \text{ kg/week} \quad 1$$

$$\text{USL}_{\text{feed}} = 7 \times 17 \text{ kg/day} \times 7 \text{ days} = 833 \text{ kg/week} \quad 2$$

The Hospitality waste stream averages 373 kg/week with $\sigma \approx 92$ kg/week, often below the feeding LSL and sometimes above the USL. This mismatch arises because waste is a by-product of guest activity, not intended to meet feeding specs, making classical process capability indices (C_p and C_{pk}) less relevant. These limits show utilisation: below LSL, extra feed is needed; above USL, surplus goes to bokashi. Capability metrics can be used for interpretation once feeding policies and nutritional needs are set. Still, it should be carefully assessed, as they reflect alignment with a biological need rather than controllable production quality.

9.5.2 Bokashi subsystem

The Staff village stream has no significant lower limit, as any positive inflow fits into the fermentation process without operational issues. The key design focus is the upper specification limit (USL), the maximum weekly mass the facility must handle to prevent landfill diversion. The USL is based on empirical data, using SPC results for statistical support. With a mean of 503 kg/week and $\sigma \approx 190$ kg/week, the three-sigma upper control limit is approximately:

$$UCL_{3\sigma} = \mu + 3\sigma \approx 1\,285 \text{ kg/week} \quad 3$$

The design point is set to handle 99.7% of inflows if the process stays in control. A conservative threshold can be set at the 95th percentile (793 kg/week) plus a safety factor based on engineering judgment or risk tolerance.

Classical process capability indices cannot be computed for bokashi since the upper limit is a design variable. Instead, capability is determined by choosing a USL to make landfill overflow rare, based on observed distribution and SPC behaviour.

9.5.3 Implications

These considerations underscore a critical distinction within the realm of validation: In the context of livestock, capability refers to the extent to which an unmanaged waste stream meets biological intake thresholds. Conversely, for bokashi, capability guides the formulation of an upper specification limit to prevent landfill overflow. Consequently, the parameters derived from SPC not only substantiate process stability but also provide quantitative data essential for engineering design decisions within the expanded circular-economy model.

9.6 Scenario analysis

The scenario analysis extends previous statistical foundations to assess circular system performance under realistic and stress-tested conditions. It uses week-type clusters from SPC and bootstrap-validated bokashi coefficients to incorporate parameter uncertainty in system evaluation. Low-load, Average-load, and Peak-load scenarios reflect inflow variability over a 26-week dataset, guiding design envelopes for capacity, buffer needs, curing infrastructure, and horticultural demand in both weekly and seasonal operations.

9.6.1 Weekly steady-state behaviour

Table 19 presents the scenario-specific inflows relevant to the hospitality sector, which serve as the foundational loading parameters for the livestock subsystem. These values quantify the

weekly volume of recoverable food waste conveyed to livestock feeding operations within each distinct scenario.

Table 19 Hospitality-derived livestock inflows across scenario clusters

Scenario	Mean inflow (kg/wk)	Median inflow	SD (kg/wk)	Min	Max
Low-load	245.8	263.7	37.4	185.1	274.9
Average-load	393.4	407.5	65.3	292.9	486.7
Peak-load	510.5	510.5	28.9	490.0	530.9

Table 19 shows a steady increase in hospitality inflows across scenarios, indicating that the livestock modelling load structure reflects real operational variability. Average-load conditions are predominant, while Peak-load is a critical stress case observed in two high-intensity weeks.

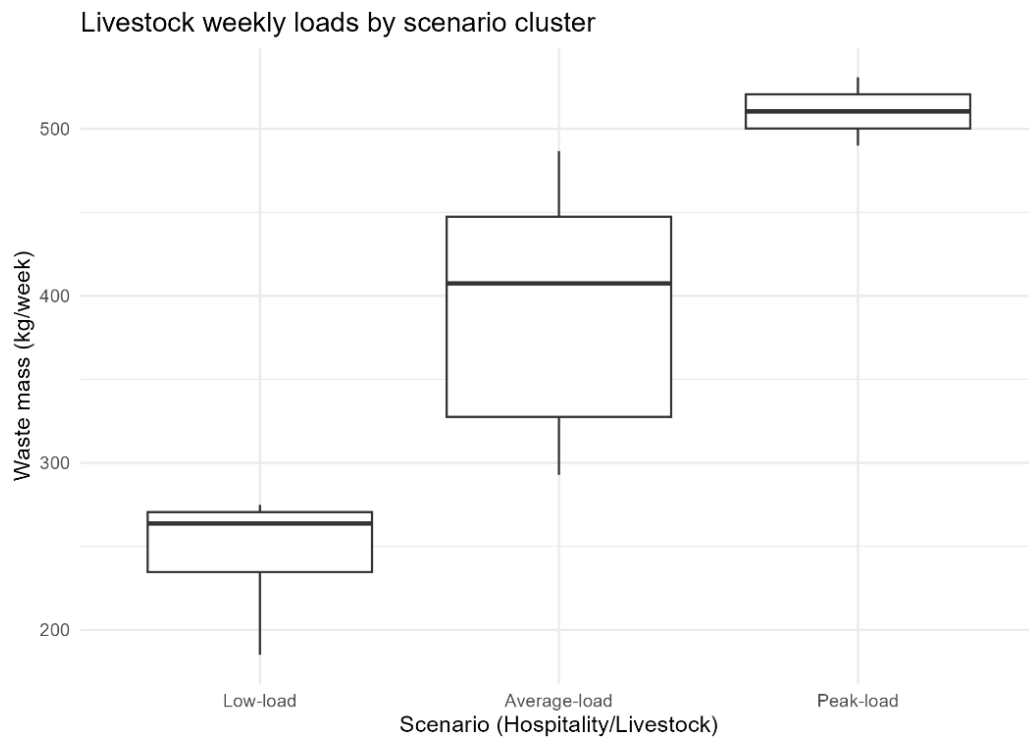


Figure 22 Boxplots of weekly inflows for Livestock

To illustrate how inflows contribute to subsystem loading, the distributions of weekly hospitality and staff village waste streams were summarised using boxplots for each scenario cluster. Figures 22 and 23 illustrate the statistical dispersion of weekly inflows.

Boxplots show distinct clusters: Low-load with lower hospitality and village inflows, Average-load around the dominant SPC-derived week-type, and Peak-load with higher medians and more dispersion. These define the weekly operational envelope for subsystems. Notably, the Peak-load cluster has no outliers beyond the SPC limits, confirming the feasibility of scenario construction.

Employing coefficients validated through bootstrap methods, the outputs of weekly bokashi processes, namely cured mass, leachate, and bran requirement, were systematically modelled for each scenario. Figure 24 shows boxplots of the distributions of potential weekly outputs for each scenario.

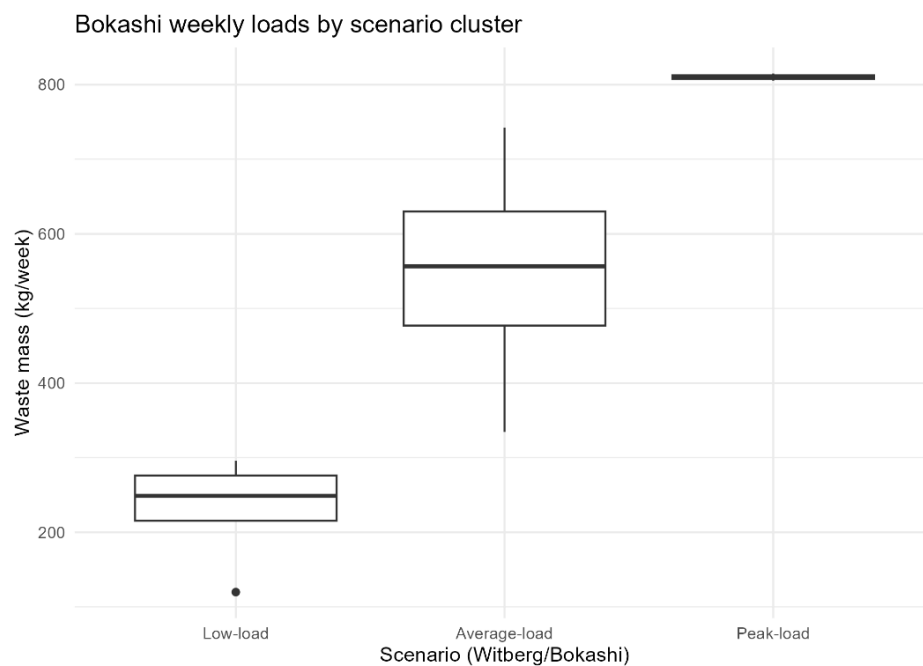


Figure 23 Boxplots of weekly inflows for Bokashi

Weekly bokashi outputs under Low-, Average-, and Peak-load scenarios

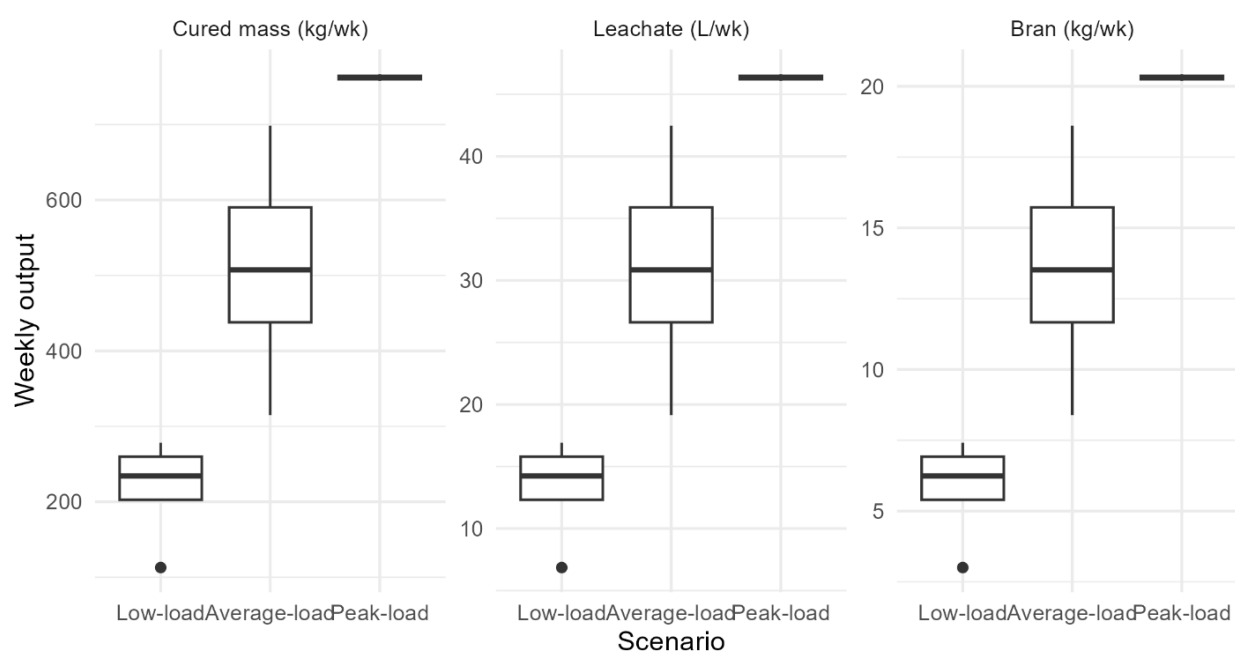


Figure 24 Weekly Bokashi outputs

Bin requirements and sensitivity

The forecasted weekly outcomes of the bokashi process for each operational scenario facilitate the assessment of curing-bin utilisation, work-in-progress (WIP) inventory accumulation, and the demand for horticultural nutrient application. Table 20 provides a summary of these steady-state parameters, using the validated conversion coefficients as detailed in Section 9.3, assuming a curing period of 2 weeks and a standard bin capacity of 1,000 kg.

Table 20 Steady-state bokashi outputs, WIP accumulation, and bin requirements across scenarios

Scenario	Bokashi inflow (kg/wk)	Cured mass (kg/wk)	Leachate (L/wk)	Bran use (kg/wk)	WIP mass (kg)*	Bins required	Garden area (m ² /wk)
Low-load	339	319	19-22	7.5-8.0	640	1	158
Average-load	641	603	34-37	14-16	1,200	2	158
Peak-load	815	765	42-47	18-21	1,530	2	158

Table 20 shows that curing-bin use depends mainly on the amount and variability of bokashi inflow. In Low-load conditions, a weekly cured mass of ~319 kg accumulates to ~640 kg WIP over two weeks, fitting within a single 1,000 kg bin, ensuring continuous curing. Average-load

scenarios produce ~603 kg weekly, raising WIP to ~1.2 tonnes, necessitating two bins to maintain flow stability. Peak-load scenarios increase WIP to ~1.53 tonnes, confirming the need for two bins to prevent overflow. Under peak conditions, two bins provide a buffer, eliminating the need for additional bins. Garden-area demand stays constant at ~158 m²/week due to fixed nutrient rates, unaffected by inflow changes.

Bin recommendations remain robust under operational uncertainty. A sensitivity analysis shows no need for a third bin. Thus, a two-bin setup is conservative and resilient, managing variability and peak loads without risking WIP buildup. This confirms that the bokashi system effectively handles waste generation at The Reserve, ensuring continuous processing and stable nutrient flows, supporting the circular food-waste model's resilience.

9.6.2 Seasonal capacity translation

The infrastructure sizing must be robust for a production “season.” Weekly outputs for each scenario were extrapolated to a 13-week horizon for planning food production and waste management. Seasonal cured-mass, leachate, and bran needs were derived from scenario-specific weekly averages and validated conversion coefficients. Figure 25 shows seasonal cured-mass totals for Low-, Average-, and Peak-load scenarios, against the curing capacity for one- and two-bin setups.

Figure 25 shows the seasonal cured-mass output for the Low-, Average-, and Peak-load scenarios as a function of curing capacity. Orange bars depict the total cured mass over 13 weeks per scenario, and blue bars show the maximum throughput of installed bins with a 1,000 kg volume and a two-week curing period.

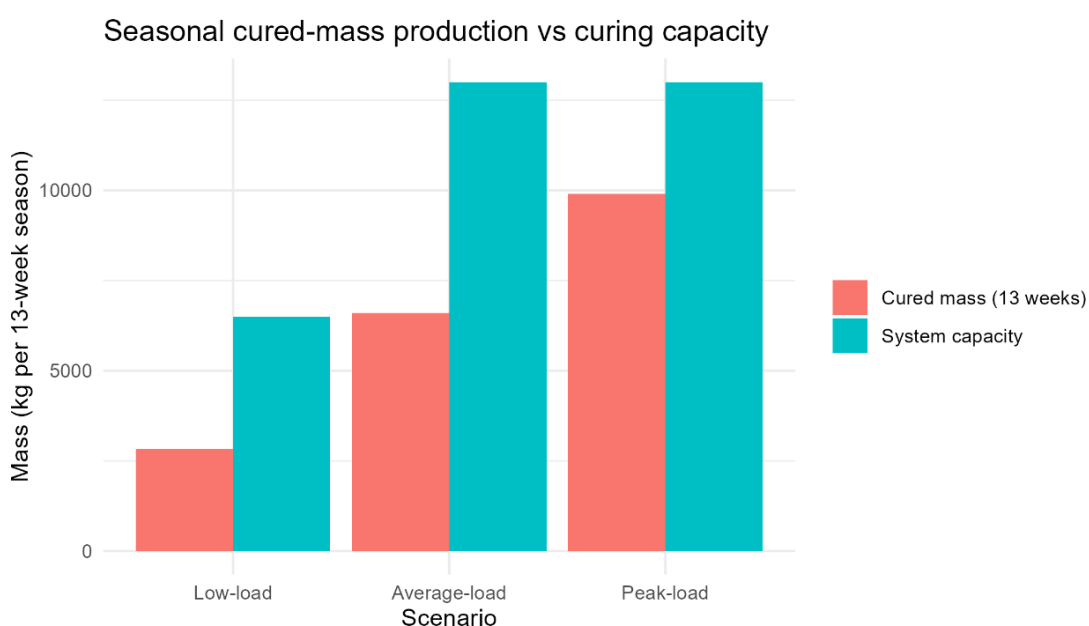


Figure 25 Seasonal cured-mass production and curing capacity under Low-, Average- and Peak-load scenarios

Table 21 provides the underlying seasonal figures.

Table 21 Seasonal translation of bokashi outputs, garden-area requirements, bin utilisation and curing-capacity margins.

Scenario	Mean Bokashi inflow (kg/wk)	Cured mass (kg/season)	Leachate (L/season)	Bran use (kg/season)	Garden area (m ² /season)	Bins in operation	System capacity (kg)
Low-load	≈ 231	≈ 2 830	≈ 170	≈ 75	≈ 1 420	1	6 500
Average-load	≈ 540	≈ 6 600	≈ 400	≈ 180	≈ 3 300	2	13 000
Peak-load	≈ 810	≈ 9 900	≈ 600	≈ 260	≈ 5 000	2	13 000

The garden area is quantified as the total area capable of amendment at a rate of 2 kilograms per square meter per week throughout a 13-week growing season, contingent upon the application of cured bokashi as a singular seasonal intervention.

Cured mass production increases almost linearly with intensity, from 2.8 t in the Low-load to 9.9 t in the Peak-load scenarios. A single 1,000 kg bin suffices for Low-load, with a 3.7 t margin on a 6.5 t capacity. For Average- and Peak-load, two bins are needed, providing a 13 t capacity with margins of 6.4 t and 3.1 t, avoiding saturation even with high inflows. Leachate and bran need to scale with output while remaining manageable. Garden areas for amendment grow from 1,400 m² in Low-load to 5,000 m² in Peak-load, allowing higher amendment rates or more plots. The

two-bin setup at The Reserve is conservative, handling variability and high loads, ensuring reliable long-term operation of the food-waste valorisation model.

9.6.3 Interpretation and design implications

Weekly and seasonal scenario analyses show that the Reserve's bokashi subsystem operates stably, with adequately sized infrastructure, across the full range of observed inflow variability. The near-linear relationship between bokashi inflow and cured-mass output ensures high predictive reliability, even under random fluctuations in inputs. This linearity clarifies the subsystem's scaling: proportional increases in waste inflow yield proportional increases in cured output, with no signs of nonlinear thresholds or tipping points.

The scenario analysis is therefore a robust tool for assessing scaled operations, allowing the model to set and adjust circularity requirements for each process in a transparent, iterative framework. By testing performance under Low, Average, P95, and Peak inflow conditions, the model determines the necessary capacity, curing area, and throughput as inflows rise, ensuring circular-economy performance can be consistently maintained without system-level disruption.

The seasonal translation supports subsystem stability across all scenarios, with positive curing-capacity margins. The two-bin setup processes 6.6 to 13 tonnes per season and maintains a 3.1-tonne margin even at peak loads, showing infrastructure resilience. This ensures no organic material exits the circular pathway due to excess load or discharge.

The evidence indicates that a fortnightly two-bin curing schedule is not only adequate but also strategically conservative. It ensures continuous material flow, aligns with garden nutrient needs, and maintains biological nutrient recirculation. This system effectively converts food waste into productive inputs, supporting the reserve's circular-economy model. Hence, the bokashi unit is well-suited for long-term use, aiding The Reserve's goal of a resilient, locally closed circular agri-food system.

9.7 Integrated model validation: Material flow analysis and circular value stream mapping

Previous sections confirmed the functionality of individual subsystems: livestock, bokashi, and garden, through variable control charts, bootstrap, and scenario testing. This section consolidates these findings by validating the integration of all components into a unified circular system. Integration ensures material closure, balanced mass flows, and aligned process timing, storage, and use. Following Material Flow Analysis (MFA), each subsystem is assessed as a node for material flow, accumulation, or product exit (Brunner and Rechberger, 2016; Dulo et al., 2022).

Circular Value Stream Mapping visually represents subsystem interactions, confirming operational synchronisation (Kalemkerian et al., 2023). These tools validate the model as a coherent CE system, aligning with DSR goals to demonstrate the utility of the artefact (Peffer et al., 2007).

9.7.1 Material flow analysis

Material Flow Analysis (MFA) was applied to quantify the circulation of organic material across the livestock, bokashi, and horticulture subsystems under three distinct operational scenarios. Due to the steady-state nature described by MFA, distinct MFA tables were formulated for Low-load, Average-load, and Peak-load conditions. This differentiation facilitates a direct comparison of circularity performance across baseline, representative, and high-stress inflow conditions.

Figure 26 shows an MFA diagram of the circular food-waste valorisation model. The system's topology remains constant; only the magnitudes of the material flows change across scenarios. As per Brunner and Rechberger (2016), the diagram displays system boundaries, processes, and closed-loop pathways of the circular architecture, with scenario-specific flow intensities detailed in subsequent tables.

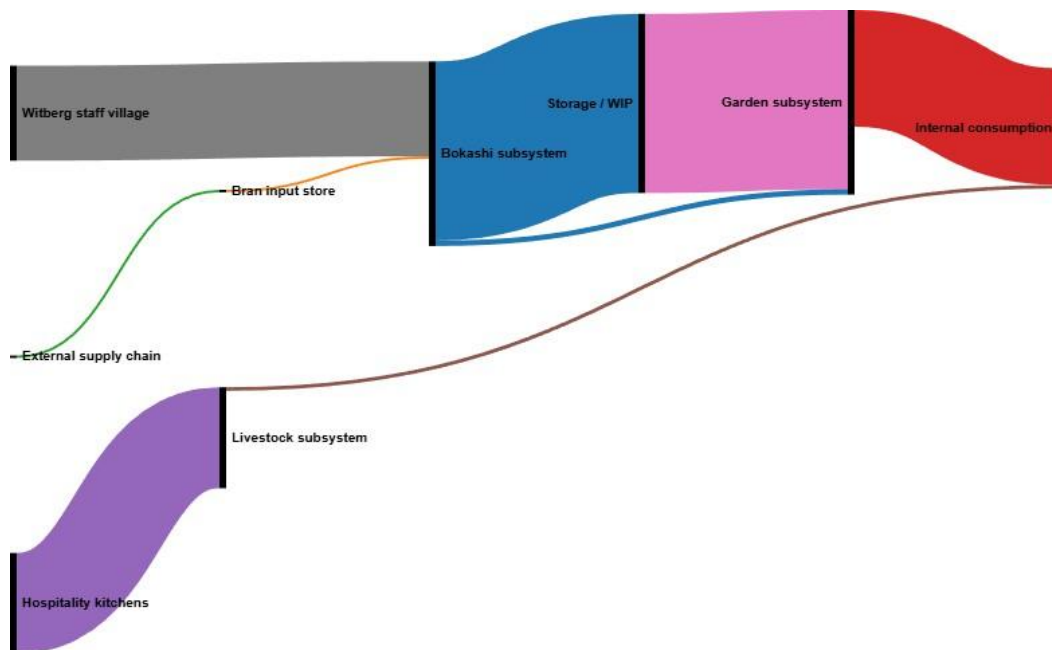


Figure 26 Material Flow Analysis diagram of the circular food-waste valorisation system

The MFA diagram uses an Internal consumption node instead of a closed loop for livestock and garden outputs to the Hospitality kitchens and the staff village. This decision is necessary because the distribution of pork, vegetables, and herbs is not recorded or separable in the organisation's datasets; both groups share a standard supply system with varying consumption. Allocating

outputs to specific groups would require unverifiable assumptions, undermining MFA's methodological robustness. Thus, the circular model aggregates products into a single node, ensuring mass balance and accuracy. Brunner and Rechberger (2016) imply using aggregated nodes when systems do not differentiate between flows, aligning with established MFA practices and maintaining analytical integrity.

Table 22 shows weekly material flows in the circular system under Low-load conditions, with Hospitality and village inflows below the SPC-defined average minus one standard deviation. These weeks have reduced guest presence and lower staff-village activity, representing the least demanding conditions. The table summarises significant internal flows: livestock feed intake, bokashi production, leachate generation, bran use, WIP accumulation, and horticultural outputs, depicting the steady state of minimal inflows and conversion demands.

Table 22 Material flows under Low-load steady-state conditions

Source	Target	Flow description	Flow value (kg/wk)	Notes / coefficient basis
Hospitality kitchens	Livestock subsystem	Food waste as feed	245.8	Mean hospitality inflow, Low-load
Livestock subsystem	Internal consumption	Pork meat	8.8	Equivalent to two 115 kg pigs over ± 26 weeks
Staff village	Bokashi subsystem	Source-separated organic waste	231	Mean Village inflow, Low-load
Bokashi subsystem	Storage / WIP	Work-in-progress bokashi mass	436	2-week retention $\times$ 218 kg cured/wk
Bokashi subsystem	Garden subsystem	Leachate (liquid nutrient)	13.2	Scenario mean; bootstrap-validated coefficient
Storage / WIP	Garden subsystem	Cured bokashi soil amendment	436	Released fortnightly from WIP
Bran input store	Bokashi subsystem	Bokashi bran inoculant	5.8	$0.025 \text{ kg/kg} \times 231 \text{ kg input}$
Garden subsystem	Internal consumption	Vegetables and herbs	284	Steady weekly production replacing imports

External supply chain	Bran input store	Purchased bokashi bran	6	Assumed equal to weekly consumption
Landfill	-	Avoided disposal of village organics	-231	Full diversion of village waste

Under Low-load conditions, the system processes 0.48 tonnes of organic material weekly: 245.8 kg from Hospitality and 231 kg from the staff village stream. Despite reduced inflow, it ensures complete material closure by converting organics into livestock feed, bokashi, leachate, or horticultural amendments, with no landfill disposal. The Bokashi subsystem remains stable, producing 218 kg of cured product per week and maintaining a 436 kg WIP inventory under a 2-week retention requirement. External dependency is low, with only 5.8 kilograms of bran entering weekly. This scenario shows efficient resource utilisation, ample slack capacity, and no process bottlenecks in the circular model under light operational loading.

Table 23 illustrates weekly steady state material flows under Average-load conditions, which are the central operational state at The Reserve. Combining 393.4 kg/wk from Hospitality and 544 kg/wk from the staff village, the table shows the interactions among the livestock, bokashi, and garden subsystems at normal intensity, aiding in validating weekly performance, capacity alignment, and circular efficiency.

Table 23 Material flows under Average-load steady-state conditions

Source	Target	Flow description	Flow value (kg/wk)	Notes/coefficient basis
Hospitality kitchens	Livestock subsystem	Food waste as feed	393.4	Mean hospitality inflow, Average-load
Livestock subsystem	Internal consumption	Pork meat	8.8	As above, biological throughput unchanged
Staff village	Bokashi subsystem	Source-separated organic waste	544	Mean village inflow, Average-load
Bokashi subsystem	Storage / WIP	Work-in-progress bokashi mass	1 024.0	2-week retention × 512 kg cured/wk
Bokashi subsystem	Garden subsystem	Leachate (liquid nutrient)	31.1	Scenario mean
Storage / WIP	Garden subsystem	Cured bokashi soil amendment	1 024.0	Fortnightly release

Bran input store	Bokashi subsystem	Bokashi bran inoculant	13.6	$0.025 \text{ kg/kg} \times 544 \text{ kg input}$
Garden subsystem	Internal consumption	Vegetables and herbs	284	Weekly horticultural output
External supply chain	Bran input store	Purchased bokashi bran	14	Assumed equal to weekly consumption
Landfill	—	Avoided disposal of village organics	-544	Full diversion of village waste

Under Average-load, the system processes about 1 tonne of organic material weekly, indicating high activity in hospitality and staff operations. The bokashi subsystem processes 544 kg/week, yielding 512 kg of cured product, and maintains a 1.02-tonne WIP inventory, confirming the two-bin setup is suitable for continuous operation. Increased load does not affect circularity; all material is absorbed, and landfill diversion remains 100%. Bran consumption rises but stays minimal (<15 kg/week). Horticultural outputs are stable at 284 kg/week. Overall, the Average-load MFA shows a balanced, efficient, fully circular material pathway.

Table 24 outlines the system-wide weekly material flows during peak-load weeks, the most demanding observation periods. These occur when village inflows exceed the 95th percentile and Hospitality inflows exceed the SPC thresholds, pushing the conversion subsystems to their limits. This scenario evaluates whether subsystem capacities, retention times, and inter-node dependencies remain balanced under intense waste generation.

Table 24 Material flows under Peak-load steady-state conditions

Source	Target	Flow description	Flow value (kg/wk)	Notes/coefficient basis
Hospitality kitchens	Livestock subsystem	Food waste as feed	510.50	Mean hospitality inflow, Peak-load
Livestock subsystem	Internal consumption	Pork meat	8.80	As above, animals constrain throughput
Staff village	Bokashi subsystem	Source-separated organic waste	810.00	Mean village inflow, Peak-load
Bokashi subsystem	Storage / WIP	Work-in-progress bokashi mass	1 524.0	2-week retention × 762 kg cured/wk
Bokashi subsystem	Garden subsystem	Leachate (liquid nutrient)	46.30	Scenario mean
Storage / WIP	Garden subsystem	Cured bokashi soil amendment	1 524.0	Fortnightly release
Bran input store	Bokashi subsystem	Bokashi bran inoculant	20.30	0.025 kg/kg × 810 kg input
Garden subsystem	Internal consumption	Vegetables and herbs	284.00	Garden sized to constant demand
External supply chain	Bran input store	Purchased bokashi bran	20.00	Assumed equal to weekly consumption
Landfill	–	Avoided disposal of village organics	-810.00	Full diversion of village waste

The Peak-load scenario manages 1.32 tonnes of organic waste weekly, with high bokashi (810 kg) and livestock (510.5 kg) inflows. The bokashi system yields 762 kg of cured material and 1.52 tonnes of WIP, fitting within the two-bin curing capacity. Despite increased load, the system avoids overflow or the need for landfill use. Livestock receive sufficient feed, and horticultural outputs remain stable as the garden is sized to meet dietary needs. External inputs are minimal at 20.3 kg of bran weekly. This confirms the system's resilience and circularity, maintaining waste diversion, synchronisation, and process continuity even under peak loads.

Under conditions characterised by low, average, and peak loads, MFA shows that circularity is consistently maintained, with complete redirection of food waste away from landfills across all examined scenarios. The operational synchrony of the livestock-bokashi-garden cycles is preserved even as the load intensity increases. Although WIP escalates substantially during peak load, it remains within the capacity constraints of the existing infrastructure, thereby affirming the robustness of the design. The internal consumption of pork and vegetables offers an alternative to external food procurement, thereby enhancing local circularity. This evidence bolsters

validation by demonstrating that the artefact maintains material closure and operational circularity under stress conditions, thereby fulfilling the Design Science Research (DSR) criteria that require the solution to be functional and reliable in the face of realistic system variability.

9.7.2 Circular value stream mapping

The Circular Value Stream Map (CVSM) offers a comprehensive system-level perspective on the interactions between organic waste, information, and biological processes within an integrated circular supply model. Unlike the MFA, which focuses on quantifying mass flows, the CVSM incorporates a temporal dimension that includes value-added (VA) time, non-value-added (NVA) time, and biological lead time. Moreover, it delineates the decision-making processes and feedback loops that are crucial to synchronising these flows. This methodology enhances traditional Lean Value Stream Mapping by extending its applicability to the circular-economy framework, accounting for factors such as regenerative delays, complex multi-loop interactions, and the dynamics of recirculating flows, as articulated in the studies by Marquina et al. (2021) and Kalemkerian et al. (2023).

Figure 27 illustrates the CVSM for the empirically validated model, encapsulating both the Hospitality-Livestock feedback loop and the Village-Bokashi-Garden nutrient-recycling loop within a cohesive temporal framework. Organic waste originating from hospitality kitchens and the staff residential area is systematically collected bi-daily and directed to their designated subsystems. The bokashi subsystem necessitates a 14-day microbial curing process, denoted as VA time, succeeded by a brief collection and loading interval not exceeding 2 days. In contrast, the garden subsystem operates on a 7-day nutrient absorption and harvest cycle, while the livestock subsystem engages in continuous metabolic conversion with a weekly cyclic output.

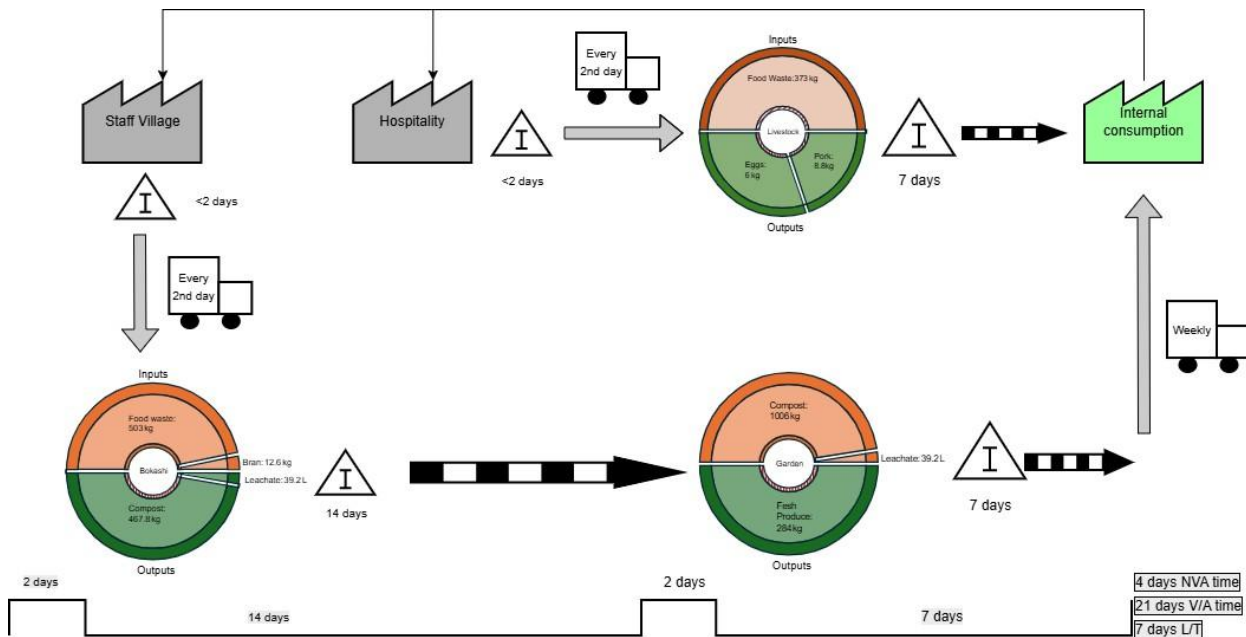


Figure 27 Circular Value Stream Map of The Reserve's circular economy model

The CVSM demonstrates the system's capacity to sustain uninterrupted weekly throughput by strategically distributing micro-batches across subsystems, despite the presence of inherently distinct biological rhythms. The inventory triangles serve as indicators of regenerative Work-In-Process (WIP) points, including incoming waste buffering with a duration of ≤ 2 days, bokashi curing with approximately 1 tonne in process, and weekly harvest accumulation amounting to approximately 284 kg. These inventories do not signify operational inefficiencies but rather reflect biologically necessitated holding times. This characteristic is increasingly acknowledged within circular supply-chain systems, as evidenced by recent literature (Vegter et al., 2020; Pereira et al., 2020).

The information-flow arrows indicate feedback mechanisms crucial to synchronisation processes. Specifically, waste-generation patterns dictate the allocation of livestock feed; the readiness of bokashi dictates the timing of nutrient application; and data on internal consumption provide insights into determining the frequency of harvesting and preparing feed. These feedback loops are instrumental in ensuring coherence between inflow variability and regenerative capacity, thereby reinforcing the model's function as a self-regulating circular system.

The CVSM consolidates all outputs at the Internal Consumption node to maintain analytical integrity, thereby avoiding speculative assumptions that arise from splitting flows. This CVSM acts as a temporal synchronisation map and a circular-economy process model, ensuring cohesive subsystem operation and embedded circularity in the waste-valorisation system.

9.8 Validation through circular key performance indicators

To enhance validation procedures grounded in MFA and CVSM, an array of circular Key Performance Indicators (KPIs) was used to quantitatively assess the artefact's efficacy under varying load conditions: Low, Average, and Peak. These KPIs evaluate the system's proficiency in waste diversion, organic material valorisation, external input substitution, and the maintenance of efficient, compliant resource flow management. The indicators are conceptually inspired by the Circularity Gap Report (2025) and the existing literature on the circular bioeconomy, with necessary modifications tailored to the practical constraints of a decentralised conservation site. This context precludes the feasibility of continuous life-cycle inventory (LCI) and multi-stakeholder accounting processes, as assumed under ISO 59020:2024.

The application of identical indicators across three distinct loading scenarios facilitates an evaluation that transcends mere absolute performance, enabling an analysis of system sensitivity. This encompasses alterations in circularity as input loads fluctuate, subsystems near biological capacity thresholds, and infrastructural limitations impact mass balance. The subsequent Table 25 delineates the results for each scenario relative to benchmark targets and provides interpretative explanations when indicators surpass or fail to meet the established nominal thresholds.

Table 25 Scenario results

KPI	Target	Low-load	Average-load	Peak-load	Rationale / Interpretation
Waste-diversion rate (%)	≥ 80%	100%	100%	100%	Organic waste from Hospitality and the village is sent to livestock or bokashi, with none going to landfill, supporting the Reserve's strategy to eliminate organic disposal.
Waste-conversion rate (%)	≥ 60%	113%	89%	83%	Conversion >100% at low load occurs because both secondary (bokashi outputs) and tertiary (vegetables, pork) products are counted. Secondary outputs scale with inflow, but tertiary outputs remain fixed, so the ratio declines as load increases.
Resource-efficiency ratio (kg/kg)	≥ 80%	61%	31%	22%	Inputs encompass all mass entering the system, with outputs being only edible produce. Efficiency drops as the pigs are used for waste stabilisation rather than production. Limited slaughter and garden space reduce edible yield, while greater inflow increases mass retention in soil or during fermentation. This metric overlooks long-term soil benefits.
Secondary-material substitution rate (%)	≥ 50%	52%	52%	52%	Garden output depends on cultivated area and crop productivity, not waste inflow. Substitution is constant across scenarios, reflecting realistic replacement of purchased produce.
System Performance Index (SPI)	≥ 70	92	83	81	The composite index remains high across all scenarios, with a decline in loading indicating reduced resource efficiency near capacity limits. All SPI values surpass the benchmark, affirming the artefact's resilience and performance under stress.

The KPI results show the circular model performs well under all loading conditions, maintaining 100% waste diversion by treating all food waste internally. MFA diagram and CVSM confirm no organic waste outflows and closed routing. The waste conversion efficiency surpasses 60% and can exceed 100% in low-load scenarios due to the simultaneous operation of multiple valorisation pathways. Specifically, secondary bokashi outputs are combined with fixed tertiary outputs, such as vegetables and pork. While secondary outputs scale proportionally with the inflow, tertiary outputs remain constant, leading to a decline in overall efficiency as the load increases. This phenomenon is indicative of the system's design rather than a measure of inefficiency, as inflow increases, conversion moderates, with some material becoming long-term soil matter. Resource efficiency drops from 61% at Low-load to 22% at Peak-load due to fixed capacities in the livestock and horticulture subsystems.

At The Reserve, pigs serve as a waste sink rather than a continuous production system, reducing edible outputs but enhancing diversion efficiency. The substitution rate remains at 52%, indicating that garden productivity depends on area and yields, not on waste inflow. SPI values of 92, 83, and 81 indicate high circularity, even at Peak-load, with modest declines due to resource-efficiency drops, but all values exceed the 70 benchmark, proving the system's robustness and stability.

9.9 6R paradigm benchmarking

The conceptual robustness of the artefact can be further illustrated by situating it within the 6R framework, which comprises the following principles: Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture. According to established CE frameworks, these six principles serve as fundamental pathways for economic systems to transition from linear to circular material flows (Kirchherr et al., 2023; Asante et al., 2022).

Table 26 below correlates each "R" with specific design features of the current model, elucidating how the system implements the principle and identifying any gaps where the principle is less applicable in the context of organic waste.

Table 26 Mapping the 6R Paradigm to the CE model's features

"R"	Definition	Implementation within The Reserve's model	Comment / Gaps
Reduce	Reduce input and waste at source.	Waste streams are measured, sorted, and treated rather than sent to landfills.	Direct behavioural interventions are enabled, not modelled.
Reuse	Reuse items/materials without reprocessing.	Limited in organic waste due to food safety and biological constraints.	Non-organic packaging reuse lies outside this subsystem's scope.
Recycle	Recycle waste for reuse in the same or similar function.	The bokashi system turns organic waste into compost and leachate.	Despite being a robust pathway, horticultural output is not entirely recycled material.
Recover	Extract value from waste: energy, nutrients, materials.	Livestock and bokashi processes recover nutrients and bioproducts.	Recovery is key to system design and waste elimination.
Redesign	Revise the design to minimise waste and enhance circulation.	The system architecture is redesigned with segregation, multi-loop pathways, and an internal consumption node.	This is a fundamental design shift, not incremental optimisation.
Remanufacture	Refurbish products to original or enhanced value.	Not applicable in bio-waste systems, but nutrient loops aid in restoring function.	The principle is less relevant here, but the narrative can reflect similar 'nutrient remanufacture'.

Positioned within the 6R paradigm, the system emphasises circularity through Recycle, Recover, and Redesign, reinforcing its role beyond waste management to a circular system (Kirchherr et al., 2023). While Reduction is not yet prominent, it is facilitated by measurement and feedback for future upstream interventions. Reuse is limited by the biological nature of the waste, thereby avoiding exaggerated claims of circularity. Remanufacture is less applicable in this organic context, but nutrient regeneration provides a viable alternative narrative. The 6R table functions as a diagnostic and strategic tool, clarifying which circular aspects are addressed and their depth, and highlights trade-offs and system boundaries where context limits certain "Rs."

9.10 Summary

Chapter 9 validated the circular economy model for The Reserve using four evidence strands: statistical inflow analysis, bootstrapped coefficient validation, scenario-based performance testing, and system-level evaluation via Material Flow Analysis, Circular Value Stream Mapping and Circular Key Performance Indicators. These analyses confirmed the model's technical coherence and sustainable operation within the Reserve's constraints.

Data analysis showed stable statistical properties for hospitality and the staff village waste streams, supporting SPC-derived scenario construction. Bootstrap regression validated Bokashi subsystem coefficients, ensuring scalability. Scenario analysis assessed operational implications and showed positive capacity buffers across all scenarios. Scenario results offered design insights, not forecasts, demonstrating system resilience.

The MFA demonstrated a high degree of material closure and nutrient retention, whereas the CVSM corroborated process synchronisation across all subsystem interactions. The KPI assessment additionally evidenced complete diversion from landfill and high conversion efficiencies. Across all investigated scenarios, the model exhibited robust circularity performance, with the System Performance Index consistently surpassing 70 points.

The artefact is structurally robust, exhibits predictable behaviour, and demonstrates resilience, thereby eliminating the need for organic waste disposal and contributing to the internal demand for fresh produce. While the model enhances operational decision-making by quantitatively characterising material flows, capacity requirements, and scaling behaviour, it does not constitute a complete Decision Support Tool. Instead, it provides a rigorously validated analytical basis to inform managerial decision-making and strategic planning in circular food waste management.

CHAPTER 10

10 Conclusion

This chapter summarises the study's purpose, methodology, and main findings, showing how it addressed the Kalahari Reserve's core sustainability challenge: the tension between its conservation ethos and landfilling organic waste. The Reserve's dependence on imported food intensified this issue, highlighting the need for a regenerative system that reduces environmental impacts and enhances local self-sufficiency. To meet this dual challenge, the study designed a circular economy model for on-site organic-waste valorisation, tailored to the operational, ecological, and infrastructural realities of a remote eco-tourism reserve.

The research pursued this overarching aim through five sequential objectives. The first objective, establishing a comprehensive understanding of circular economy principles, Industrial Engineering methodologies, and waste-management practices in conservation contexts, was achieved via a narrative literature review that provided the conceptual foundations necessary for subsequent system design. The second objective, namely the derivation of design and legal requirements for a circular economy model, was realised through a structured scoping review of the academic literature and relevant South African environmental legislation, culminating in a codified register of design constraints, enablers, and context-specific specifications. The third objective, designing a theoretical model, was achieved by constructing an integrated artefact comprising livestock feeding, bokashi fermentation, and horticultural production as interdependent subsystems capable of closing material loops. The fourth objective, verifying the artefact, was met by evaluating its semiotic and functional adequacy using the SEQUAL framework, together with alignment to circular-economy and waste-management standards. Finally, the fifth objective, model validation, was satisfied through a multi-layered empirical programme incorporating bootstrap coefficient estimation, Statistical Process Control, scenario and sensitivity analysis, Material Flow Analysis, Circular Value Stream Mapping, and circular Key Performance Indicators. Together, these methods assessed process stability, yield reliability, subsystem synchronisation, and circularity performance under realistic operational conditions.

The validated artefact achieved complete diversion of waste from landfill, full bioconversion of organic residues, a resource-efficiency ratio of 99%, a secondary-material substitution rate of 53%, and a System Performance Index of 93%. Collectively, these performance metrics substantiate that decentralised circular food-waste management systems can function with high predictability and efficiency in arid conservation landscapes, thereby enabling protected areas to lower reliance on external inputs while maintaining ecological integrity.

Beyond its practical implementation at the Kalahari Reserve, this study contributes to Industrial Engineering by showing how Lean, Circular Economy, and Bio-economic paradigms can be integrated through MFA, CVSM, and KPI-based validation. It also provides a methodological basis for engineering circular bio-economy models in the Global South, demonstrating how context-sensitive circular interventions can be designed, calibrated, and validated in ecologically fragile, resource-constrained settings. The remainder of this chapter elaborates on the study's contributions, acknowledges its limitations, and considers the broader implications for sustainability transitions in conservation-linked socio-ecological systems.

10.1 Research overview

The study investigated the challenge posed by organic waste generated by eco-tourism operations being diverted to landfill, thereby compromising the reserve's sustainability objectives. An engineered intervention was designed to close biological nutrient cycles within the infrastructural and ecological constraints characteristic of a semi-arid environment, employing Design Science Research as the methodological framework. First, a narrative literature review was conducted to establish a conceptual foundation on the circular economy, organic-waste valorisation pathways, and the application of Industrial Engineering methodologies in conservation contexts. This review supported the formalisation of the problem, the delineation of system boundaries, and the identification of knowledge and implementation gaps in circular-agriculture interventions for ecologically sensitive and resource-constrained settings.

Second, a structured scoping review of academic literature and South African environmental legislation yielded a codified register of technical, legal, organisational and ecological requirements. This requirements catalogue informed the design of a context-appropriate circular economy model tailored to the Kalahari Reserve. Third, these requirements were consolidated into a theoretical artefact comprising three interdependent subsystems: bokashi fermentation, livestock feeding, and horticultural production, forming a decentralised circular system that transforms organic waste into food, compost, and animal feed. The artefact was operationally adapted to the specific processes of the Reserve, and pilot studies on bokashi fermentation and livestock feeding generated empirical coefficients for subsequent model calibration. Fourth, the artefact was verified using the SEQUAL framework and by assessing its alignment with circular-economy and waste-management standards, thereby establishing its semantic, pragmatic, organisational, and technical adequacy prior to empirical validation.

Finally, a multi-layered validation programme was implemented: bootstrap regression was employed to validate subsystem coefficients under parameter uncertainty; statistical process control was used to assess waste-stream stability; scenario clustering and week-type modelling

were applied to evaluate system capacity under variable loading conditions; and material flow analysis, circular value stream mapping and circular key performance indicators were used to quantify material closure, subsystem synchronisation, and circularity performance. Collectively, these phases demonstrate that small-scale, decentralised circular systems can be systematically engineered, calibrated, and validated to operate in a predictable, resource-efficient manner in remote ecotourism environments, thereby converting organic waste from an environmental liability into a regenerative resource.

10.2 Contributions

This study links theory and practice in Circular Economy and Industrial Engineering by demonstrating how engineered systems can enhance biodiversity conservation and community resilience, and it offers a validated circular-economy model for on-site organic-waste valorisation in a remote eco-tourism reserve. The model integrates livestock feeding, bokashi fermentation, and horticultural production into a decentralised circular economy tailored to semi-arid, resource-limited conservation settings. Empirical calibration and multi-layered validation show that the system can achieve full waste diversion, nutrient recycling, and partial food self-sufficiency in situ, addressing the sustainability challenges in the problem statement. The study also advances Industrial Engineering by showing how engineering design principles, circular-economy theory, and ecological constraints can be combined within a structured Design Science Research process to create context-appropriate solutions for resource-constrained environments. These contributions span academic literature, organisational practice, and individual capability development.

10.2.1 Contribution to literature

This research contributes to the academic field in several ways, including a validated circular-economy model for conservation settings that offers a documented system architecture and empirical evidence demonstrating how closed-loop food-waste systems can be engineered for remote, semi-arid reserves; the integration of established Industrial Engineering tools in ecological contexts, showing how MFA, CVSM, SPC, scenario analysis, and circular KPIs can be adapted for biological and conservation-linked systems rather than traditional industrial environments; a codified register of , derived from literature and environmental legislation, that provides a structured set of requirements future researchers can apply when designing circular systems in similar contexts; and an applied example of DSR in the Global South, demonstrating how DSR can guide the design, contextualisation, verification, and validation of a sustainability-oriented engineering artefact in a non-industrial domain, with these combined contributions

helping to extend the role of Industrial Engineering into sustainability transitions and ecological infrastructure development.

10.2.2 Contribution to organisations

The study generates demonstrable organisational-level value by presenting a tested, operationally feasible model for organic-waste valorisation that provides conservation organisations with a viable mechanism to eliminate landfill disposal and reduce reliance on externally procured animal feed, compost, and horticultural produce. In addition, it yields calibrated parameters, material flow rates, capacity requirements, and system performance indicators that can inform operational planning and reporting.

Furthermore, the model facilitates alignment with prevailing regulatory and sustainability frameworks by supporting compliance with South African environmental legislation (e.g., the National Environmental Management: Waste Act (NEMWA) and the National Environmental Management: Biodiversity Act (NEMBA)) and by aligning organisational operations with broader biodiversity conservation and circular-economy objectives. Owing to its modular architecture and parameterisation, the model is capable of being adapted to context-specific protected areas, other conservation landscapes, remote tourism lodges, and semi-arid communities seeking to implement circular bioeconomy or circular-economy interventions.

10.2.3 Contribution to individuals

The implementation and operation of the circular economy model additionally generate benefits at the individual level. Personnel engaged in the system acquire applied competencies across multiple subsystems: bokashi fermentation, livestock nutrition, and horticultural production, thereby developing a broad, cross-functional technical skill set that transcends conventional operational roles. Their involvement in monitoring waste input streams, formulating feed mixtures and schedules, managing fermenter operating cycles, and supporting crop production enhances their understanding of resource fluxes, process interdependencies, and the theoretical and practical principles that underpin circular system design and functioning.

In addition to acquiring technical proficiency, operators gain exposure to fundamental principles of operational planning and localised decision-making. Through routine coordination of inputs, outputs, and subsystem timing, individuals engage in informal yet structurally analogous scheduling, sequencing, and resource allocation that reflect core competencies in Industrial Engineering. Although the broader socio-economic impacts of these activities were not formally evaluated in this dissertation, the experiential learning inherent in managing a decentralised circular system appears to foster the development of operational self-efficacy, autonomy, and

systems-level reasoning. These individual-level outcomes contribute to human capacity development in remote conservation contexts, thereby enhancing personnel's ability to participate substantively in sustainability-oriented practices and institutional resource governance.

10.3 Limitations and future research

Although the artefact exhibited sufficient technical and environmental performance, several limitations persist that justify further investigation to enhance its long-term applicability, transferability, and organisational integration. First, the study adopted a linear modelling framework based on empirically calibrated material flows, proportional scaling assumptions, and week-type scenario clustering. This approach was appropriate given the relatively stable, non-feedback behaviour observed in the waste streams. More advanced modelling paradigms, such as System Dynamics for exploring reinforcing and balancing feedback loops, Discrete Event Simulation for representing subsystem interactions over time, and Design of Experiments for systematically analysing multivariate sensitivities, were beyond the scope of this dissertation. These methodologies could enable the representation of temporal delays, batch-duration effects, seasonal variability, and nonlinear responses that may arise as the system is scaled up or as additional subsystems (e.g., renewable energy, water recycling) are incorporated.

Second, the research concentrated predominantly on technical and operational validation. Societal, behavioural, and institutional dimensions, including user acceptance, organisational culture, adoption readiness, and sustained staff engagement, were not systematically investigated, despite their critical importance for the successful implementation of decentralised circular systems. The enactment of circular practices inherently intersects with human factors, including training, motivation, perceived additional workload, and resistance to organisational change. Future research should therefore integrate change-management frameworks, behavioural diagnostic approaches, and/or participatory research methodologies to systematically assess how individuals and teams adopt, internalise, and maintain novel practices over extended periods.

Third, the study was implemented at the scale of a single operational site. Although the artefact exhibited strong scalability within The Reserve, its performance in broader, multi-site, or organisational contexts was not empirically assessed. Variations in staff competencies, logistical frameworks, sociocultural dynamics, and levels of organisational maturity may affect replicability. Future comparative research across multiple reserves or rural communities could evaluate the artefact's adaptability, identify key determinants of success, and further refine the model's external validity and generalisability.

Fourth, the research did not incorporate a formal techno-economic analysis, despite its critical importance for long-term decision-making. Future work should therefore integrate systematic cost-benefit analysis, payback period estimation, labour productivity modelling, and quantitative risk assessment to formulate a more robust and comprehensive business case for investment in decentralised circular systems. The inclusion of such economic evaluations would further facilitate wider organisational adoption and enhance the rigour and effectiveness of strategic planning processes.

Finally, environmental performance was assessed indirectly via material closure and circularity metrics, rather than through comprehensive life-cycle assessment (LCA) or environmental impact assessment (EIA). Future research should integrate these methodological approaches to quantitatively assess the system's contributions to greenhouse gas mitigation, nutrient cycling, and soil health enhancement, thereby establishing a more robust and comprehensive ecological profile of circular agriculture interventions in semi-arid conservation settings.

In summary, subsequent research should broaden the methodological framework to encompass dynamic modelling, economic feasibility assessments, human factors analysis, and multi-site evaluations, thereby enhancing the understanding of how circular systems function across heterogeneous ecological and organisational contexts. Collectively, these research directions would enhance the evidential and practical value of the current artefact and facilitate the wider uptake and institutionalisation of circular-agriculture practices within conservation and rural development.

10.4 Concluding remarks

Circularity in remote conservation contexts does not arise from isolated, ad hoc interventions, but from intentional system-level design sustained by continuous human participation. The model developed in this study demonstrates that, when social actors, operational processes, and ecological constraints are effectively aligned, organic waste can be transformed from a management burden into a regenerative resource that enhances socio-ecological resilience and operational self-sufficiency. The performance and durability of such systems depend not only on the physical infrastructure and technical configuration, but equally on everyday behavioural commitment and the overarching organisational ethos.

In this context, the study underscores a broader principle: sustainability is most effective when intentionally engineered, rather than treated as an abstract ideal.

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Appendix A

INTEGRATING HYDROPONIC CULTIVATION AND CIRCULAR ECONOMY PRINCIPLES FOR SUSTAINABLE FOOD PRODUCTION IN REMOTE SEMI-ARID ENVIRONMENTS: A CASE STUDY FROM THE SOUTH AFRICAN KALAHARI

Abstract

Remote conservation reserves encounter enduring logistical challenges in the provision of fresh produce and management of organic waste, particularly under the extreme water scarcity and semi-arid conditions prevalent in the Kalahari. These issues necessitate the implementation of engineered agricultural solutions that incorporate circular economy principles tailored to context-specific production systems. This article synthesizes the existing literature on circular agriculture, emphasising aspects such as bokashi composting, closed-loop nutrient cycling, and livestock integration, and contextualises these findings within a pilot study conducted at a luxury ecotourism reserve located in the southern Kalahari, South Africa. The study assessed controlled-environment agriculture (CEA) with a specific emphasis on hydroponics as a water-efficient intervention, exploring postharvest considerations including pest management, light optimisation, temperature regulation, and irrigation efficiency. Six cultivation methods, hydroponic aeroponics, deep-water culture (DWC), nutrient film technique (NFT), autopots, in addition to raised beds and bale gardening, were tested in repurposed horse stables and an outdoor net house to evaluate their suitability for semi-arid conservation settings. The pilot study demonstrated robust performance in the production of leafy greens and pest resistance, although fruiting crops were constrained by inadequate pollination and root crops by inconsistent moisture levels. These findings offer operational insights for ongoing empirical research. The integration of engineered circular agricultural systems with comprehensive postharvest strategies, including precise pest control, advanced pollination techniques, optimised irrigation scheduling, climate regulation, and customised artificial lighting, can significantly enhance resource efficiency, reduce waste, and bolster the resilience of food systems. This research contributes to the advancement of sustainable food production pathways for remote, water-scarce conservation reserves.

Keywords: hydroponics, circular economy, conservation reserves, semi-arid, sustainable food

1. Introduction

1.1. Context

Sustainable food production in remote conservation areas is increasingly challenged by factors such as water scarcity, poor soil quality, extreme climatic conditions, and logistical complexities associated with long-distance supply chains (Kumar et al., 2021; Lund et al., 2023). These issues become particularly acute in arid and semi-arid environments, such as South Africa's Kalahari region, where traditional agriculture frequently struggles to maintain consistent yields and sustainability outcomes (Goddek et al., 2023; Abedrabbah et al., 2023). In alignment with Sustainable Development Goal 2 (Zero Hunger), these constraints highlight the imperative for context-specific, resilient food production systems capable of enhancing food security while simultaneously reducing reliance on exogenous supply chains.

Hydroponic cultivation, a soilless agricultural method, has emerged as a viable and resource-efficient alternative suitable for arid regions (Kumar et al., 2021). By delivering water and nutrients directly to plant roots within controlled environments, hydroponics significantly reduces water usage, by up to 90%, compared with conventional agricultural methods (Kumar et al., 2021; Lund et al., 2023).

Additionally, hydroponic systems minimise land use requirements, reduce vulnerability to pests and diseases, and increase crop productivity by maintaining optimal environmental conditions (Tagle et al., 2018, Udovichenko et al., 2021). These attributes make hydroponics particularly well-suited for implementation in conservation-focused settings, where resource conservation and environmental protection are paramount.

Simultaneously, circular economy (CE) principles offer robust frameworks for addressing organic waste management issues prevalent in conservation areas. Unlike conventional linear waste management practices, which involve transporting waste to distant landfills, CE emphasises the transformation of waste streams into valuable resources through composting, nutrient recycling, and other regenerative processes (Ellen MacArthur Foundation, 2022, Lombardi et al., 2021). This approach not only mitigates the environmental impacts associated with waste disposal, such as methane emissions and soil contamination, but also reduces reliance on external resources such as chemical fertilisers (Brunner and Rechberger, 2016, Merfield, 2012).

The dynamics of the water-energy-food (WEF) nexus offer a critical framework for comprehending sustainability challenges in remote conservation landscapes. In semi-arid environments such as the Kalahari, water scarcity imposes limitations on both agricultural production and energy generation, while the availability of energy subsequently dictates the feasibility of water treatment, pumping, and controlled-environment agriculture (Abedrabbah et al., 2023; Goddek et al., 2023). Although energy systems in isolated reserves are predominantly reliant on diesel-based technologies, emerging low-energy agricultural innovations particularly hydroponics, present opportunities to alleviate operational demands while enhancing resource circularity (Udovichenko et al., 2021). Within this nexus, the interdependence between food and water becomes exceptionally significant: the productive capacity in soilless systems is intimately linked to the efficient utilisation of water, retention of nutrients, and management of postharvest quality. For remote conservation regions characterised by acute water scarcity, the integration of hydroponics and circular practices such as bokashi fermentation and nutrient cycling constitutes not merely an agricultural intervention but a systemic response to interrelated resource constraints.

This study employs a case study methodology centred on an eco-tourism reserve with a conservation emphasis in the southern Kalahari region of South Africa. The reserve is located within a remote, semi-arid landscape that is characterised by significant temperature fluctuations, scarce availability of surface water, and rigorous environmental protection mandates. These contextual variables impose considerable stress on operational systems, especially those associated with food production and resource management.

Due to the geographical remoteness of the case study organisation, ensuring a consistent supply of fresh produce presents considerable logistical challenges, thereby rendering on-site cultivation a strategic necessity. The region's extreme climatic conditions, presence of wildlife, issues related to water scarcity, and overarching sustainability goals have prompted the pilot study to investigate innovative cultivation methodologies that seek to optimise both productivity and resource efficiency.

A key component of this study involves transforming existing infrastructure to facilitate semi-controlled-environment agriculture. Specifically, renovated horse stables need to be adapted into a facility for semi-controlled growth. Initially intended for housing horses, these stables provide a durable and ample structure updated with artificial lighting, ventilation, and polycarbonate roofing to establish a favourable microclimate. Utilising this pre-existing resource can contribute to the organisation's sustainability and offer a dependable setup for continuous cultivation throughout the challenging climate.

Equally important is an outdoor net house at the organisation, which also provides a semi-controlled environment that takes advantage of natural light and conditions while offering protection from extreme

weather. The net house has demonstrated promising potential for growing fruit-bearing vegetables and leafy greens, while light exposure and water management adjustments are needed.

This study aligns with the organisation's broader sustainability and conservation goals of reducing dependency on imported produce, lowering the environmental impact of long-distance transportation, and contributing to local food security.

Moreover, the economic and social implications are significant; by utilising existing structures and optimising resource use, the initiative lowers operational costs and fosters local community engagement through improved food self-sufficiency.

Ultimately, the pilot study boasted in this research serves as a proof-of-concept for scaling up controlled-environment agriculture at the organisation. The insights gained from the stables and the net house are intended to lay the groundwork for future enhancements and research, setting the stage for a sustainable, high-yield, on-site food production system that addresses the region's unique challenges.

1.2. Research aim

The aim of this study is to explore the feasibility of controlled-environment agriculture (CEA) integrated with circular economy principles to address logistical challenges related to fresh produce supply and organic waste management in remote, ecologically sensitive conservation reserves.

1.3. Research objectives

The objectives are to:

- Qualitatively assess crop performance and feasibility of controlled-environment agriculture methods (namely aeroponics, deep-water culture (DWC), nutrient film technique (NFT), autopots, raised beds, and bale gardening)
- Assess and comparatively analyse the general resource demands (water, energy, sunlight)
- Identify qualitative challenges and limitations associated with each cultivating system.
- Propose theoretical recommendations for integrating circular economy principles based on observed strengths and limitations of each method.

The remainder of this paper is structured as follows. The Literature Review synthesises prior research on hydroponic cultivation in arid environments, the integration of circular-economy principles in agricultural systems, and controlled-environment agriculture within conservation-oriented contexts. The Methodology section describes in detail the experimental design, study sites, and cultivation systems employed in the pilot study. The Results section reports the performance of the cultivation systems across the two environmental settings, followed by a Discussion that compares and interprets these outcomes with reference to circular-economy frameworks and overarching system-level constraints. The paper concludes by outlining recommendations for system optimisation, considerations for upscaling and replication, and priority areas for future research in remote conservation settings.

2. Literature review

This section critically reviews existing literature on hydroponic cultivation, circular economy principles in agriculture, and sustainable food production strategies in conservation areas. These themes provide the theoretical foundation necessary for proposing an integrated system suitable for remote conservation environments.

2.1. Hydroponic cultivation in semi-arid environments

Hydroponics is a soil-less agricultural system in which plants are grown using nutrient-rich water solutions, directly supplied to their roots. This cultivation method significantly reduces water consumption, making it particularly suitable for arid and semi-arid regions (Kumar et al., 2021). Research has shown hydroponic systems can achieve up to 90% water savings compared to traditional soil-based agriculture due to efficient water recirculation and controlled nutrient delivery (Lund et al., 2023).

The effectiveness of hydroponics in challenging environments, such as desert climates, is well-documented. Goddek et al. (2023) highlight that controlled-environment agriculture (CEA), including greenhouse hydroponics, can mitigate extreme temperatures and water scarcity, facilitating consistent crop yields in otherwise inhospitable regions. Similarly, Abedrabboh et al. (2023) demonstrated that hydroponic systems successfully maintained stable growing conditions in urban desert environments similar to Doha and Cairo, suggesting the adaptability of these systems to a wide range of climatic challenges.

Moreover, hydroponics maximises space utilisation, allowing high-density planting and year-round crop production, irrespective of external climatic conditions. Tagle et al. (2018) observed robust performance of leafy greens grown in hydroponic towers, noting accelerated growth and improved nutritional quality. Udovichenko et al. (2021) further support these findings, illustrating commercial viability and environmental sustainability of vertical hydroponic farms through reduced land footprint and increased crop density.

Greenhouse horticulture, which often incorporates hydroponics, has proven effective in arid regions offering climate-resilient and sustainable food production systems (Goddek et al., 2023). In the southern Kalahari, where extreme weather limits traditional agriculture, greenhouses can enhance yield and quality even under suboptimal conditions (Ferguson et al., 2014). The commercial feasibility of greenhouse hydroponics, particularly for high-density planting, supports its scalability in conservation areas (Udovichenko et al., 2021).

2.2. Environmental Control and Management in Controlled-Environment Agriculture

Maintaining optimal environmental conditions is critical for hydroponic systems in arid regions. Greenhouse designs could incorporate effective thermal and humidity management to ensure crop productivity. Goddek et al. (2023) emphasise the importance of water-based cooling systems, such as evaporative cooling, to control temperature and increase humidity in arid climates. Abedrabboh et al. (2023) suggest that combining natural ventilation with 50% shading nets can effectively lower greenhouse temperatures, offering an energy-efficient alternative to mechanical cooling systems. Tsafaras et al. (2021) further note that exhaust fans, pad walls, and direct or indirect evaporative cooling systems can regulate temperature and humidity, though they may increase water consumption. For example, cooling systems can account for up to 90% of water use in vegetable cultivation, highlighting the need for efficient water management (Goddek et al., 2023). Strategic ventilation, such as aluminised polyester sheets to reduce solar radiation, can further enhance energy efficiency and maintain stable growing conditions (Abedrabboh et al., 2023; Tsafaras et al., 2021).

Artificial lighting plays a pivotal role in controlled environments, particularly in settings like renovated horse stables where natural sunlight is limited. LED lighting, which emits specific wavelengths in the red (600–650 nm) and blue (400–500 nm) spectra, supports photosynthesis and regulates growth stages, such as flowering and vegetative development (Teng et al., 2024). These systems enable year-round production by compensating for variable natural light, with adjustable intensity and photoperiods enhancing biomass and nutritional content (Weidner et al., 2021; Chiaranunt & White, 2023).

2.3. The circular economy: conceptual foundations and performance metrics

The circular economy (CE) presents a transformative alternative to the traditional linear economy model, which follows a 'take-make-dispose' sequence. In contrast, CE focuses on extending resource lifecycles by designing out waste, keeping products and materials in use for as long as possible, and regenerating natural systems (Ellen MacArthur Foundation, 2022). This systems-thinking approach has gained traction in both policy and industry due to its ability to simultaneously address environmental degradation, resource scarcity, and economic inefficiency (Geissdoerfer et al., 2018).

In the context of agricultural and conservation systems, CE principles are operationalised through practices such as organic waste valorisation, composting, nutrient cycling, and integration of livestock for regenerative purposes. These interventions aim not only to reduce reliance on external inputs such as synthetic fertilisers, but also to eliminate the environmental burden associated with linear waste disposal methods (Brunner & Rechberger, 2016; Merfield, 2012).

To evaluate the effectiveness of circular strategies, performance must be measured through relevant indicators. The Circle Economy (2025) introduces a suite of CE metrics that quantify material circularity across system boundaries. These were adapted in the current study to assess the performance of a proposed circular food system model designed for conservation reserves.

The Key Performance Indicators (KPIs) used in this model, summarised in Table 1 KPI's for circularityTable 1 below, were selected based on their alignment with both global best practices and South African national policy targets. Specifically, they reflect benchmarks set by the National Waste Management Strategy (DEFF, 2020), the National Environmental Management: Waste Act (NEMWA, 2008), and technical performance ranges cited in circular agriculture and CE supply chain literature (Lombardi et al., 2021, FAO, 2017, Circle Economy, 2025).

TABLE 1 KPI'S FOR CIRCULARITY

KPI	Definition	Target	Data Source
Waste-diversion rate (%)	Share of organic waste redirected from landfill through reuse, composting, or feed production	$\geq 80\%$	Material Flow Analysis (MFA)
Waste-conversion rate (%)	Proportion of diverted waste converted into usable products such as compost or liquid feed	$\geq 60\%$	Production logs
Resource-efficiency ratio (kg/kg)	Output (edible or usable biomass) per kilogram of input resource mass	$\geq 80\%$	MFA & Value Stream Mapping (VSM)
Secondary-material substitution (%)	Percentage of commercial fertilisers or feeds replaced with on-site alternatives	$\geq 50\%$	Procurement & operational records
Controlled-disposal rate (%)	Share of residual waste safely managed via engineered landfills or compliant disposal	100%	Landfill compliance documentation
Reserve-level circularity metric (%)	Share of secondary materials in the total material inflows of the reserve's systems	$\geq 25\%$	Consolidated MFA

System performance index (SPI, 0–100)	Composite score based on normalised values of diversion, conversion, substitution, and efficiency	≥ 70	Weighted average of above KPIs
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The KPI thresholds represent a balanced intersection between aspirational global benchmarks and locally feasible targets. The waste-diversion target of $\geq 80\%$ is informed by the NWMS (2020), which sets ambitious national goals for reducing organic landfill volumes. Similarly, a 100% controlled-disposal rate reflects the Waste Act's compliance requirement for all non-recyclable residuals to be handled via licensed facilities.

The resource-efficiency and waste-conversion rates ($\geq 80\%$ and $\geq 60\%$, respectively) are derived from performance ranges reported in circular food systems literature, especially within decentralised or semi-urban applications (Lombardi et al., 2021; FAO, 2017). These benchmarks reflect realistic outcomes in systems where material reuse, composting, and yield optimisation are implemented with basic infrastructure and moderate training.

The secondary-material substitution rate ($\geq 50\%$) reflects the expected reduction in virgin input demand when systems such as bokashi composting and livestock integration are fully operational. This is particularly relevant in conservation areas where transport costs and chemical fertiliser usage are sustainability concerns (van der Velden et al., 2022).

Lastly, the reserve-level circularity metric and SPI serve to synthesise multiple indicators into overarching system-wide measures. The SPI, a composite index normalised to a 0–100 scale, offers a concise representation of system performance across four weighted categories (diversion, conversion, substitution, and efficiency). A threshold of ≥ 70 was chosen based on performance modelling in similar CE-integrated agrifood systems (Circle Economy, 2025).

2.3.1 Circular economy in agricultural systems

The circular economy (CE) approach emphasises the sustainable management of resources by transforming waste streams into valuable inputs, thus reducing environmental impacts and resource dependency (Ellen MacArthur Foundation, 2022). Central to the CE model are principles of reducing waste, reusing materials, recycling nutrients, and regenerating ecosystems, which are particularly relevant to agricultural systems.

Merfield (2012) identifies composting, including anaerobic methods such as Bokashi fermentation, as effective mechanisms for converting organic waste into valuable soil amendments. Bokashi composting retains nutrient density, mitigates greenhouse gas emissions, and rapidly converts food waste into usable compost, making it suitable for remote and resource-limited locations (Merfield, 2012). A useful output of bokashi composting is a nutrient dense leachate that could be diluted in hydroponic systems' water reservoirs to be use by the cultivated plants. Brunner and Rechberger (2016) also highlight that nutrient recycling, facilitated through techniques such as Material Flow Analysis (MFA), can systematically identify waste management inefficiencies, enabling precise interventions to maximise resource reuse within closed-loop agricultural systems.

Additionally, integrating livestock such as pigs and chickens into agricultural CE systems has been explored extensively. Livestock integration effectively valorises organic waste as animal feed, reducing waste disposal challenges and enhancing nutrient recycling (Swanepoel and Smit, 2025; Rööfs et al., 2017). Such systems enhance sustainability by producing valuable outputs (meat, eggs, manure) while simultaneously managing waste streams effectively, thereby reducing external resource requirements and ecological footprints (Demichelis et al., 2025).

2.4. Industrial engineering methodologies for circular economy integration

Industrial Engineering (IE) offers a comprehensive, systems-based methodology for addressing sustainability challenges by integrating technical optimisation with environmental and social considerations (Parnell and Kenley). As Roopa et al. (2024) assert, the discipline has evolved well beyond its traditional roots in manufacturing and logistics to become pivotal in sustainability-driven transformations.

According to Tsoku et al. (2024), IE is uniquely positioned to contribute to sustainability by enhancing resource efficiency, reducing environmental impacts, and improving social outcomes through integrated system design and optimisation. They argue that IE's systems thinking approach, defined by the integration of people, processes, and technology, directly supports the achievement of multiple Sustainable Development Goals (SDGs), particularly SDG 12 (responsible consumption and production), SDG 9 (industry, innovation and infrastructure), and SDG 7 (affordable and clean energy). The South African context is especially pertinent, as local IE curricula are increasingly aligned with these global goals through graduate attributes enforced by the Engineering Council of South Africa (ECSA), which require sustainability considerations in engineering problem solving and design (Tsoku et al., 2024).

Industrial engineers deploy analytical and diagnostic tools such as Material Flow Analysis (MFA) and Value Stream Mapping (VSM) to quantify and visualise resource flows, identify inefficiencies, and redesign processes to eliminate waste and close material loops (Lombardi et al., 2021, Tsoku et al., 2024). These tools are instrumental in circular economy applications, especially in decentralised, resource-constrained contexts. In such environments, IE methodologies enable the development of adaptive waste management solutions that enhance operational efficiency while maintaining ecological sensitivity (Roos et al., 2023, Mukwevho et al., 2024).

Furthermore, Tsoku et al. (2024) demonstrate that IE principles, such as systems integration, supply chain sustainability, human-centred design, and life-cycle cost analysis, map directly onto the core pillars of sustainable engineering: environmental stewardship, economic feasibility, and social equity. These capabilities position industrial engineers as key enablers in designing resilient systems tailored to the nuanced constraints of conservation reserves.

2.5. Implementation Considerations for Conservation Areas

The successful implementation of integrated circular-hydroponic systems in remote conservation areas extends beyond technical viability. It requires careful consideration of local socio-economic dynamics, institutional capacity, and logistical constraints. While the literature confirms the environmental and operational benefits of closed-loop food systems, their long-term success depends heavily on local stakeholder engagement, system adaptability, and ongoing management support (Roos et al., 2023; Nanda & Firmansyah, 2017).

One critical factor is the need for community and staff participation. In ecotourism reserves, food production systems often depend on daily interaction from non-specialist staff such as maintenance teams, lodge workers, and conservation personnel. Without adequate training and a shared sense of ownership, systems may deteriorate due to inconsistent application of nutrient protocols, poor hygiene, or neglect of monitoring routines (Ragazzi et al., 2014). Therefore, capacity building through workshops, operational manuals, and continual coaching is essential to ensure procedural compliance and system longevity.

Another key consideration is infrastructure availability and service access. Conservation areas are frequently located far from urban centres, with limited access to suppliers, technical services, and spare parts. System design must therefore prioritise simplicity, modularity, and the use of locally available

materials where possible (Ahamed et al., 2023). This is especially relevant for waste treatment infrastructure, such as anaerobic digesters or bokashi fermentation units, which require minimal maintenance and can operate without grid connectivity.

Biosecurity and food safety are additional concerns, particularly when integrating organic waste streams into nutrient supply chains. Improper handling of compost or liquid fertiliser can introduce pathogens or heavy metals into the food system. To mitigate these risks, protocols must be developed for safe waste collection, pre-treatment, and storage, supported by periodic microbial and chemical testing (Salemdeeb et al., 2017).

Lastly, implementation must align with the broader conservation strategy of the reserve. Food systems should enhance, not compete with, biodiversity objectives. For example, avoiding genetically modified crops, reducing reliance on fossil-based plastics, and minimising runoff from hydroponic systems are all measures that support ecological integrity (Roos et al., 2023).

By considering these multidimensional factors, human, technical, logistical, and ecological, circular-hydroponic systems can be designed not just as efficient subsystems, but as integrated components of the conservation landscape. This systemic approach increases the likelihood of adoption, resilience, and long-term sustainability in the unique context of ecotourism facilities.

3. Methodology

The project involved a collaborative effort among researchers, each focusing on different crop categories, including tomatoes, peppers, leafy greens, and selected root vegetables, to comprehensively evaluate available technologies. The study started by searching current academic literature on the above-mentioned vegetables and how they are being cultivated and promising new technologies being employed in horticulture.

Experiments were conducted in two distinct venues: a renovated horse stable and an outdoor net house, which offered partial exposure to natural elements while still affording some protection against the region's extreme conditions and wildlife. The study evaluated different cultivation methods, including aeroponics, deep-water culture (DWC), nutrient film technique (NFT), autopots, raised beds, and bale gardening, to determine their practical viability and long-term sustainability.

The renovated equestrian stables were chosen for their ability to prevent baboon entry. These stables were retrofitted with artificial lighting (though not of premium quality) ventilation systems, white-painted walls, and polycarbonate panels on the roof's east side, allowing for additional light exposure. Additionally, a water reservoir and irrigation system were installed. In contrast, the second site was an outdoor net house that offered a semi-controlled environment. This venue allowed for partial exposure to natural conditions while still providing protection against extreme weather and pests, thereby facilitating a comparison between artificial and more natural growing conditions.

The study evaluated six cultivation methods: aeroponics, deep water culture (DWC), nutrient film technique (NFT), autopots, raised beds, and bale gardening. Aeroponics was tested for its water efficiency and capacity to promote rapid plant growth. Deep water culture (DWC) was employed for its simplicity. A three-tier nutrient film technique (NFT) system was trialled primarily to explore its potential for oxygenating the water compared to DWC. Autopots were implemented for low-maintenance, water-conserving cultivation of leafy vegetables. At the same time, raised beds and bale gardening were investigated as viable techniques for growing root crops such as carrots, beetroot, onions, and potatoes. The selection of crops, including leafy greens, fruit-bearing plants such as tomatoes and peppers, and various root vegetables, was informed by their nutritional value and adaptability to controlled and semi-controlled environments.

Environmental suitability was assessed by visually and quantitatively evaluating the impact of light, temperature, and humidity on crop health. Operational challenges were documented, including system failures, pest infestations, and maintenance requirements.

The investigation aimed to understand various cultivation methods by systematically recording environmental, crop-specific, and operational observations. Differences in systems were due to infrastructure, environmental exposure, and method properties. Table 2 summarises the data, distinguishing between quantitative and qualitative observations, providing a basis for interpreting each system's performance.

TABLE 2 SUMMARY OF DATA COLLECTED PER CULTIVATION METHOD

Cultivation Method	Measured Environmental Data	Qualitative Environmental Observations	Crop Performance Observations	System Operational Observations
Aeroponics (Stables)	PAR spot measurement (afternoon: 171 $\mu\text{mol}/\text{m}^2/\text{s}$); Light adequacy (AM adequate; PM low)	Thermal stress indicated by leaf wilting; humidity not measured; limited airflow	Leafy greens: strong vegetative growth; fruiting crops: abundant blossoms but no fruit set	Nozzle function; reservoir condition; maintenance needs
DWC (Stables)	PAR spot measurement (afternoon: 171 $\mu\text{mol}/\text{m}^2/\text{s}$); Light adequacy (AM adequate; PM low)	Qualitative heat stress; humidity not measured; limited airflow	Leafy greens: strong growth; fruiting crops: flowering without fruit formation	Aeration performance; algae presence; reservoir clarity
NFT (3-tier) (Stables)	PAR spot measurement (afternoon: 171 $\mu\text{mol}/\text{m}^2/\text{s}$); Light adequacy (AM adequate; PM low)	No quantitative environment data; shading between tiers	Poor seedling establishment; weak vegetative growth	Structural instability; flow interruptions; channel drying
Autopots (Stables)	PAR spot measurement (afternoon: 171 $\mu\text{mol}/\text{m}^2/\text{s}$); Light adequacy (AM adequate; PM low)	Qualitative heat stress; humidity not measured	Leafy greens: good performance; fruiting crops: constrained by light/pollination	Capillary line blockages; reservoir contamination (algae, insects)
Raised Beds (Stables)	PAR spot measurement (afternoon: 171 $\mu\text{mol}/\text{m}^2/\text{s}$); Light adequacy (AM adequate; PM low)	Qualitative light limitation (PM low); heterogeneous bed moisture	Carrots/onions/potatoes: restricted tuber/bulb formation; beetroot: good biomass	Soil moisture distribution issues; irrigation consistency
Bale Gardening (Stables)	PAR spot measurement (afternoon: 171 $\mu\text{mol}/\text{m}^2/\text{s}$); Light adequacy (AM adequate; PM low)	Qualitative light limitation; uneven moisture penetration	Poor establishment, low biomass; poor root crop formation	Bale wetting issues; decomposition rate; structural stability

Soil Beds (Net House)	Weekly water use: $\approx 2\,000$ L/week (reservoir refill measurement)	Natural light under shade net (qualitative assessment: insufficient for root crops)	Leafy greens and chillies: good performance; root crops: poor	Irrigation delivery variability; drainage behaviour
Net House Irrigation (Manual Hose)	Weekly water input measured (2 000 L/week)	Over-/under-watering symptoms observed	Indirect effects on all crops	Reservoir refill frequency; labour intensity
Pest Monitoring (Both Sites)	None measured	Whitefly presence in stable; low pest pressure in net house	Crop impact minimal	None
Pollination Observation (Stables)	None measured	No pollinators; limited airflow	Blossoms present, fruit set absent	Identification of manual/mechanical pollination need

The distribution of data across varying cultivation methods reveals significant differences in the quality and nature of the empirical data generated by each system. Hydroponic systems, implemented within the refurbished stables, allowed for a more comprehensive characterisation of environmental suitability, particularly concerning light availability and its effects on both vegetative growth and reproductive development. Conversely, the net house provided more substantial insights into water-use patterns and crop adaptability under partially controlled outdoor conditions. Across all systems, the prevalence of qualitative indicators underscores the exploratory nature of the pilot study and the infrastructural constraints inherent in the remote study environment. Despite these limitations, the aggregated dataset provides a coherent framework for assessing system reliability, crop performance, and environmental responsiveness. This analysis facilitates the identification of methods with the potential for scale-up and refinement in analogous semi-arid conservation settings.

4. Results

After the chosen cultivation systems were implemented at Tswalu, an evaluation was conducted to assess performance based on several key parameters. This section analyses the outcomes for both the refurbished horse stables and the outdoor net house, followed by a comparative discussion and concluding with future recommendations.

4.1. Results from the stables

4.1.1 Light and Photoperiod

Morning light conditions within the refurbished horse stable initially appeared sufficient for most crops, yet afternoon light levels dropped significantly. According to an expert botanist (van Niekerk, 2024), tomatoes, peppers, and chillies require a minimum of $600\ \mu\text{mol}/\text{m}^2/\text{s}$ for optimal growth, whereas measurements in the stable revealed only $171\ \mu\text{mol}/\text{m}^2/\text{s}$ in the afternoon. This shortfall indicates that additional lighting or enhanced light management is necessary to meet the recommended photoperiod, especially for fruit-bearing crops. Although more tolerant, leafy greens could also benefit from improved light intensity later in the day.

4.1.2 Pollination Challenges

Fruit-bearing plants (tomatoes, peppers, and chillies) produced abundant blossoms but failed to set fruit. Contributing factors included limited natural airflow, a lack of pollinators, and no systematic manual

pollination. Although these crops are self-pollinating, pollen transfer from the stamens to the pistils was insufficient, resulting in no fruit formation despite the abundant blossoms.

4.1.3 Heat Pressure

An additional challenge observed in the stable was significant heat pressure. During the afternoon, plants were subjected to excessive heat stress, likely due to inadequate cooling measures within the controlled environment.

4.1.4 System Performance and Technological Insights

Six cultivation methods were assessed in the stable environment: aeroponics, deep water culture (DWC), nutrient film technique (NFT), autopots, raised beds, and bale gardening.

Aeroponics and DWC: Demonstrated strong system performance regarding leafy greens, with effective nutrient delivery and consistent growth conditions, but struggled to support the weight of fruit-bearing vegetables.

NFT System: The three-tier NFT setup encountered significant operational issues, including poor seedling establishment and inadequate structural support, which affected overall system stability.

Autopots: The system generally maintained operational efficacy; however, sporadic obstructions within the capillary feed lines resulted in irregularities in nutrient delivery. Open reservoirs served as attractants for insects and facilitated algal proliferation, consequently leading to blockages at the outlets.

Bale Gardening: The observed limitations in facilitating plant development are presumably attributable to environmental constraints, including suboptimal light exposure and uneven moisture distribution.

Raised Beds: The experimental conditions maintained a stable growth environment; however, variability was observed in system efficiency. The species *Daucus carota* (carrots), *Allium cepa* (onions), and *Solanum tuberosum* (potatoes) exhibited constrained tuber and bulb development. In contrast, *Beta vulgaris* (beetroot) demonstrated optimal biomass accumulation.

4.1.5 Pest Management

The absence of an effective pest management strategy led to white fly infestations across multiple systems in the stable. However, this pest causes no significant damage to the overall plant's health.

Overall, while the stable's semi-controlled environment provided consistency for leafy greens, insufficient afternoon light, poor pollination, and occasional system-specific problems limited the success of fruit-bearing and root crops.

4.2. Results from the net house

4.2.1 Crop Performance

The outdoor net house, offering partial exposure to natural conditions, displayed notable success with leafy greens and certain fruit-bearing vegetables, particularly chillies. However, root vegetables such as carrots, onions, and potatoes struggled, likely due to inadequate light exposure. This outcome indicates that improving light management (for instance, by using lighter shade nets) could enhance root crop performance.

4.2.2 Water Usage

Manual irrigation using a watering hose currently consumes approximately 2,000 litres per week. This was measured by the frequency of refilling a 2000 L reservoir. This high usage rate underscores the need for more efficient water management solutions, such as drip irrigation or other targeted delivery methods.

4.2.3 Pest Management

Unlike the stable, the net house showed minimal pest pressure. The open design and natural airflow may have helped mitigate infestations. This low incidence of pests suggests that the net house environment could be well-suited for scaling up production, provided that other limitations, particularly light intensity and water efficiency, are addressed.

In summary, while the net house lacks the controlled consistency of the stables, it proved advantageous for certain crops (leafy greens, chillies) and demonstrated minimal pest challenges. The primary areas for improvement revolve around optimising light conditions for root vegetables and adopting more water-efficient irrigation practices.

4.3. Comparison and synthesis

When comparing the stables and the net house, each site presents distinct advantages and drawbacks:

4.3.1 Environmental Control

The stables offer a more controlled setting with artificial lighting, modified ventilation, and shading. However, afternoon light levels remain insufficient for fruit-bearing crops, and pollination challenges persist due to limited airflow. The net house benefits from natural light, which contributed to successful yields of chillies and leafy greens, but inconsistent light conditions hindered root crop development.

4.3.2 Water and Irrigation

The stables rely on systems such as aeroponics, DWC, and autopots, which, while water-efficient, require vigilant maintenance to prevent blockages and pest infestation. The net house uses manual irrigation at a rate of 2,000 litres per week, indicating an urgent need for water-saving measures such as drip irrigation.

4.3.3 Pest Management

White flies were problematic in the stables due to the absence of an integrated pest management plan, whereas the net house experienced minimal pest issues.

4.3.4 Crop-Specific Performance:

Leafy greens thrived in both environments, although the hydroponic conditions supported rapid growth in aeroponic and DWC systems. Fruit-bearing crops, especially tomatoes and peppers, failed to set fruit in the stable due to insufficient light and pollination, while chillies in the net house fared better. Root vegetables faced challenges in both settings but showed moderate success in raised beds in the stable.

These findings indicate that no single site or method perfectly addresses all crop needs. Instead, a targeted approach, optimising light, pollination, water use, and pest management in each location, will be key to achieving sustainable, high-yield on-site production.

5. Discussion

The findings from this study offer valuable qualitative insights into the feasibility and operational dynamics of controlled-environment agriculture (CEA) within remote conservation settings, particularly regarding resource efficiency and potential integration with circular economy (CE) principles.

5.1. Interpretation of Key Findings

The pilot study revealed distinct strengths and weaknesses for each cultivation environment, informing practical considerations for scaling up local food production. The renovated horse stables demonstrated consistent environmental control benefits, especially for leafy greens cultivated through aeroponics and

deep-water culture (DWC) systems. Conversely, significant challenges were identified, including inadequate afternoon lighting, pollination issues, and heat stress, which impacted the feasibility for fruit-bearing and root crops.

In contrast, the outdoor net house offered more natural light exposure and significantly lower pest pressures, particularly beneficial for chillies and leafy greens. However, root crops struggled due to insufficient and inconsistent light management. Moreover, water use efficiency emerged as a critical challenge due to high weekly consumption rates attributed to manual irrigation methods.

Table 3 summarises key strengths, limitations, and proposed interventions for each cultivation environment.

TABLE 3 SUMMARY OF RESULTS FROM EACH CULTIVATION ENVIRONMENT

Cultivation Environment	Strengths	Limitations	Recommended Interventions
Refurbished Horse Stable	Effective for leafy greens; Strong environmental control	Poor afternoon lighting; Pollination challenges; Heat stress; Pest management issues; NFT structural limitations	Upgrade artificial lighting; Enhance ventilation and introduce manual pollination; Implement integrated pest management; Improve NFT support structures
Outdoor Net House	Natural lighting favourable for chillies and leafy greens; Low pest pressures	Insufficient light for root crops; High water consumption due to manual irrigation	Implement lighter shade nets for improved light; Transition to drip irrigation

5.1.1 Theoretical Implications for Circular Economy Integration

To contextualise the circularity potential of the system, Table 4 implements the 6-R hierarchy: Refuse, Rethink, Reduce, Reuse, Repair/Refurbish, and Recycle/Recover. The expanded framework encapsulates the principles of modern circular economy paradigms, in which advanced strategies such as Refuse and Rethink are recognized for their capacity to optimize value retention and mitigate superfluous resource flows (Jawahir & Bradley, 2016; Reike et al., 2018). Empirical investigations into circular economy interventions consistently reveal that upstream avoidance and reduction often surpass downstream recycling or recovery in efficacy, particularly within resource-constrained environments where system efficiency and simplicity are paramount (Ratner et al., 2025).

TABLE 4 APPLICATION OF THE 6-R HIERARCHY TO A CLOSED-LOOP HYDROPONIC-BOKASHI SYSTEM IN A REMOTE CONSERVATION RESERVE

R-strategy	System element	Material / energy flow	Closed-loop intervention	Expected effect on circular performance
R0: Refuse	Menu design; procurement policies	Avoidable food waste; high-impact external inputs	Refuse over-specification of menu items and highly perishable ingredients; prioritise suppliers with minimal packaging and lower embodied impact inputs	Reduces upstream resource demand and avoidable organic waste generation, lowering required system capacity

				and transport-related emissions
R1: Rethink	Overall food service and production concept	Service practices; production planning; technology mix	Rethink the hospitality-waste-production chain as a single integrated system: design portion sizes, buffet practices, and cropping plans jointly with hydroponic capacity and bokashi throughput	Shifts the system from end-of-pipe waste handling to integrated resource planning, improving alignment between waste generation, nutrient demand, and hydroponic capacity
R2: Reduce	Kitchen operations; irrigation management; energy use	Food preparation waste; water use in net house; energy in stables	Implement strict segregation of organic vs non-organic waste; optimise cutting and preparation to minimise trimmings; reduce water use through drip irrigation or timed dosing in the net house; optimise photoperiods and lighting intensity in the stables	Lowers mass of organic waste requiring treatment and reduces water and energy demand, contributing directly to higher resource-efficiency ratios
R3: Reuse	Packaging and handling logistics	Reusable crates, containers, and trays	Reuse delivery crates and containers for internal logistics (e.g. harvesting, short-term storage, in-house distribution); reuse nutrient solution where quality permits (top-up rather than full replacement)	Reduces need for new packaging materials and limits disposal volumes; extends functional life of nutrient solutions where agronomically acceptable
R4: Repair / Refurbish	Hydroponic infrastructure; stables and net-house structures	Frames, reservoirs, pumps, lighting, shade structures	Repair and refurbish existing stable infrastructure, frames, reservoirs, pumps and nets before replacement; retrofit stables with improved lighting and ventilation rather than constructing new buildings	Extends asset lifetimes, reduces embodied material and construction impacts, and lowers capital requirements for system expansion
R5: Remanufacture / Repurpose	Existing built assets and materials	Redundant equestrian infrastructure; surplus materials	Repurpose horse stables as controlled-environment production space; repurpose existing tanks as nutrient or leachate reservoirs; repurpose organic residues (e.g. woody material) as structural growing media where feasible	Converts underutilised or obsolete assets into productive components of the food system, avoiding both demolition waste and new construction
R6: Recycle / Recover	Organic waste valorisation; nutrient cycling	Plate waste; kitchen prep waste; garden residues; greywater	Recycle organic waste via bokashi fermentation and subsequent use as livestock feed or soil amendment; recover nutrient-rich bokashi leachate as a supplementary input to hydroponic nutrient tanks after appropriate dilution and pre-treatment; recover greywater where regulations permit for non-potable uses	Closes nutrient loops, increases the share of secondary materials in input streams, raises waste-diversion and conversion rates, and reduces dependence on imported fertilisers and feeds

The transition from the traditional 3-R model to more comprehensive frameworks such as 6-R or 10-R has been extensively documented in recent scholarly literature, with researchers advocating for more detailed distinctions to address the complexities inherent in biological and agri-food systems (Zorpas, 2024; Khatami et al., 2024). Specifically, within agri-food circularity assessments, higher-order strategies such as Reduce and Rethink are given conceptual precedence, whereas Reuse, Repurpose, and Recover are more frequently applied in practical scenarios due to the inherent biological limitations of organic materials (Veloso et al., 2025; Velasco-Muñoz et al., 2021). These observations correspond with the opportunities identified in this study, where nutrient recovery from organic waste through bokashi fermentation serves as a feasible Reuse/Recycle pathway (Peng & Pivato, 2019), and the redirection of segregated organic waste into feed or compost reflects the recovery potentials highlighted in broader empirical analyses of urban and agricultural organic streams (Ddiba et al., 2022; Rimantho et al., 2023).

Collectively, the integration of the 6-R hierarchy offers a structured interpretive framework for the system, elucidating opportunities for interventions to transition from downstream waste management to upstream prevention, system redesign, and regenerative nutrient cycling. The 6-R hierarchy can then be used as a stepping stone for the higher R paradigms such as 9-R and 12-R.

5.1.2 Application of Industrial Engineering Methodologies

The theoretical application of industrial engineering methodologies, such as Material Flow Analysis (MFA) and Value Stream Mapping (VSM), provides a structured pathway for future empirical research. MFA can systematically visualise resource flows, whereas VSM could further quantify the resource flows, pinpointing inefficiencies in the system's operations and resource allocations (Lombardi et al., 2021, Tsoku et al., 2024).

The structured application of these methodologies will facilitate precise and targeted interventions in future research phases, enhancing circularity, operational and ecological sustainability and economic feasibility. Furthermore, such analytical tools provide robust frameworks for ongoing monitoring and continuous improvement, essential for long-term sustainability in remote conservation contexts.

5.1.3 Recommendations for System Improvements and Upscaling

The results explicitly inform technical and infrastructural adjustments critical to scaling up the CEA operations. Specifically, stables should prioritise lighting upgrades, improved ventilation, manual or mechanical pollination, and structured pest management plans. The net house, conversely, should prioritise the implementation of more efficient irrigation systems and optimisation of natural lighting using lighter shade nets.

A hybrid approach, leveraging the strengths of both environments, appears particularly promising. For example, the stables could serve as a dedicated area for germination, leafy green cultivation, and packing, given their controlled conditions. The net house could then focus on fruit-bearing crops such as chillies, where natural conditions offer clear advantages.

5.1.4 Limitations of the Study

It is crucial to acknowledge that the findings presented are qualitative, exploratory, and observational. The absence of numerical data, particularly labour metrics and detailed quantitative resource-use assessments limit the ability to precisely quantify system efficiency and economic viability. Furthermore, the theoretical integration of circular economy practices

was not empirically validated, indicating the necessity of further practical trials in varied environments.

6. Conclusions and recommendations

The present study elucidates the efficacy of integrating hydroponic cultivation with circular economy principles as a feasible strategy for developing sustainable food production systems within remote, semi-arid conservation regions. By tackling fundamental challenges such as water scarcity, suboptimal soil conditions, and logistical limitations, the proposed closed-loop system synergistically combines water-efficient soilless cultivation with the valorisation of organic waste through nutrient recycling.

The empirical results suggest that a hybrid configuration utilising refurbished stables for germination and leafy-green cultivation, alongside a net house for fruit-bearing crop production can augment overall system efficacy while preserving ecological integrity. This methodology mitigates reliance on externally sourced resources, diminishes transportation-induced environmental impacts, and bolsters local food autonomy.

Future research should include detailed quantitative evaluations of resource use (water, energy, labour) to enable precise cost-benefit analysis and optimisation. Empirical validation of circular economy practices, including bokashi composting and closed-loop nutrient recycling, should be prioritised. Implementing industrial engineering methodologies such as MFA and VSM in future pilots will enable systematic validation and refinement of the circular economy model specifically tailored for remote ecotourism and conservation contexts.

On a broader scale, the research exemplifies how engineering-focused system design can facilitate the transition of conservation areas toward resilient, resource-efficient food systems. The confluence of controlled-environment agriculture, waste valorisation, and context-specific operational methodologies highlights the potential for industrial engineering principles to redefine agricultural practices in remote environments.

Industrial engineering provides a transformative avenue for the modernisation of food production, demonstrating the capacity of systematic design and circular thinking to revolutionise agriculture in remote, semi-arid contexts.

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