



Exploring innovation and sustainability practices in South African research infrastructures through the Preclinical Drug Development Platform

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DECLARATION

I Thulile van Wyk declare herewith that the mini dissertation entitled Exploring innovation and sustainability practices in South African research infrastructures through the Preclinical Drug Development Platform, herewith submit to the North-West University in partial compliance with the requirements set for the degree: Master of Business Administration is my own work, has been text-edited in accordance with the requirements and has not already been submitted to any other university.

A handwritten signature in blue ink, appearing to read 'Thulile van Wyk', is written over a light blue rectangular background.

Signature

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ABSTRACT

Research infrastructures (RIs) play a critical role in enabling scientific discovery, technological development, and socio-economic progress. However, within South Africa, many RIs face persistent sustainability challenges characterised by funding volatility, regulatory complexity, skills shortages, and limited digital maturity. These structural constraints impede their ability to achieve operational stability, financial resilience, and long-term research impact. This study investigates how business model innovation (BMI) can strengthen the sustainability of South African research infrastructures, using the Preclinical Drug Development Platform (PCDDP) as an in-depth qualitative case. Guided by a critical realist paradigm and abductive reasoning, the study draws on document analysis and comparative international benchmarking to examine the key drivers, barriers, digital enablers, and strategic mechanisms influencing sustainability.

The study integrates three complementary theoretical frameworks, the Resource-Based View (RBV), Open Innovation (OI) Theory, and Business Model Innovation (BMI), to develop a holistic analytical lens suitable for non-commercial scientific research infrastructures. The findings show that the PCDDP possesses strong VRIN-aligned capabilities, including GLP-accredited infrastructure, specialised expertise, and institutional reputation; yet these strengths are undermined by systemic constraints such as capital renewal gaps, regulatory bottlenecks, and operational dependencies. Open innovation activities extend internal capabilities through strategic collaborations, although absorptive capacity is constrained by system-level fragmentation and variable digital readiness. BMI efforts are evident in-service diversification, governance refinement, and digital transformation initiatives, but remain incremental due to restricted financial autonomy and structural rigidity.

Benchmarking against leading international RIs highlights several sustainability-enhancing practices, including lifecycle funding models, digital research environments, and integrated governance frameworks. By synthesising theoretical insights with empirical findings, the study proposes a strategic framework for embedding innovation and sustainability within research infrastructures in South Africa. The research contributes conceptually by extending BMI, RBV, and OI theory to RI contexts, and practically by offering actionable recommendations for RI leaders, policymakers, and funding bodies. The study concludes that sustainable, innovation-driven research infrastructures require coherent alignment between internal capabilities, external knowledge ecosystems, and adaptable business models supported by an enabling national policy and funding environment.

Keywords: Business model innovation; research infrastructures; sustainability; digital transformation; Resource-Based View; Open Innovation; critical realism; South Africa; PCDDP; organisational capability; funding models; research governance; innovation ecosystems.

TABLE OF CONTENTS

<u>1.1 Introduction</u>	1
<u>1.2 Problem Statement</u>	1
<u>1.3 Research Aim</u>	2
<u>1.4 Research Objectives</u>	2
<u>1.5 Research Questions</u>	3
<u>1.6 Scope of the Study</u>	3
<u>1.7 Theoretical Contribution</u>	4
<u>1.8 Practical Contribution</u>	5
<u>1.9 Innovation and Sustainability in Research Infrastructures</u>	6
<u>1.10 Historical Context and Global Benchmarking</u>	8
<u>1.11 Case Study Justification – PCDDP</u>	8
<u>1.12 Conceptual and Theoretical Frameworks</u>	9
<u>Resource-Based View (RBV)</u>	10
<u>Open Innovation Theory</u>	10
<u>Business Model Innovation (BMI)</u>	10
<u>Integration of the Three Frameworks</u>	10
<u>1.13 Definition of Key Concepts</u>	11
<u>1.16 Research Design and Methodology Overview</u>	12
<u>Limitations and Delimitations</u>	13
<u>Limitations</u>	13
<u>Delimitations</u>	14
<u>1.17 Dissertation Structure</u>	14
<u>1.18 Conclusion</u>	15
<u>Abstract</u>	16
<u>Keywords</u>	16
<u>1 Introduction</u>	17
<u>2 Literature Review</u>	18
<u>Research Infrastructures</u>	18
<u>Business Models and Business Model Innovation</u>	19
<u>Sustainable Business Models</u>	19
<u>Resource-Based View (RBV)</u>	21
<u>Open Innovation (OI)</u>	23

<u>3</u>	<u><i>Theoretical Integration: RBV, OI and BMI for Research Infrastructures</i></u>	24
	<u>Why RBV Alone Is Insufficient</u>	24
	<u>Why OI Alone Is Insufficient</u>	24
	<u>Why BMI Is the Integrative Mechanism</u>	25
	<u>Integrated Argument: RBV, OI and BMI as a Composite Lens</u>	25
<u>4</u>	<u><i>Conceptual Framework: A Business Model Innovation Approach for Research Infrastructures</i></u>	26
	<u>Logic of the Framework</u>	26
	<u>Structure of the Framework</u>	26
	<u>Layer 1: Internal Capability Base (RBV)</u>	27
	<u>Layer 2: Collaborative Knowledge Ecosystem (OI)</u>	27
	<u>Layer 3: Business Model Innovation Processes (BMI)</u>	27
	<u>Relevance for Research Infrastructures in Developing Economies</u>	28
	<u>Illustrative Application to the PCDDP</u>	28
<u>5</u>	<u><i>Theoretical Contributions</i></u>	30
	<u>Contribution to Business Model Innovation Literature</u>	30
	<u>Contribution to Open Innovation Scholarship</u>	30
	<u>Contribution to Resource-Based View</u>	31
	<u>Contribution to African STI Systems and RI Scholarship</u>	31
<u>6</u>	<u><i>Practical Implications</i></u>	31
	<u>Implications for RI Managers</u>	31
	<u>Enhancing internal capabilities</u>	32
	<u>Leveraging collaborative networks</u>	32
	<u>Redesigning business models</u>	32
	<u>Implications for Policymakers</u>	32
	<u>Designing supportive funding models</u>	32
	<u>Improving regulatory alignment</u>	32
	<u>Strengthening national innovation systems</u>	33
	<u>Implications for Funders and Donors</u>	33
	<u>Prioritising capability-building investments</u>	33
	<u>Encouraging collaborative and cross-institutional projects</u>	33
	<u>Supporting business model transformation</u>	33
<u>7</u>	<u><i>Conclusion</i></u>	33
	<u>3.1 Introduction</u>	35
	<u>3.2 Research Paradigm: Critical Realism</u>	35
	<u>3.3 Research Approach: Abductive Reasoning</u>	36
	<u>3.4 Research Design: Single Case Study Strategy</u>	37
	<u>3.5 Justification for Selecting the PCDDP as the Case Study</u>	38

<u>3.6 Data Collection Methods</u>	38
<u>3.6.1 Document Analysis</u>	39
<u>3.6.2 Comparative Benchmarking</u>	39
<u>3.6.3 Search Strategy and Documentation Procedures</u>	40
<u>3.7 Document Analysis</u>	41
<u>3.8 Comparative Benchmarking</u>	44
<u>3.9 Thematic Analysis (ATLAS.ti)</u>	46
<u>3.10 Benchmarking Interpretation and Synthesis</u>	47
<u>3.11 Ethical Considerations</u>	48
<u>3.12 Limitations</u>	49
<u>3.13 Chapter Summary</u>	51
<u>4.1 Introduction</u>	52
<u>4.2 Data Sources and Collection</u>	53
<u>4.2.1 Institutional and Strategic Documentation (PCDDP)</u>	53
<u>4.2.2 National Policy and Planning Documents</u>	53
<u>4.2.3 International Benchmarking and Comparative Sources</u>	53
<u>4.2.4 Academic and Expert Literature Provided</u>	54
<u>4.2.5 Analytical Preparation and Workflow</u>	54
<u>4.2.6 Data-Management and Audit Trail</u>	54
<u>4.3 Narrative Interpretation: Overview of Findings</u>	54
<u>4.4 Themes</u>	57
Theme 1: Key Drivers of Innovation and Sustainability	58
Theme 2: Barriers to Adopting Sustainable Strategies	58
Theme 3: Role of Digital Capabilities in Financial Sustainability and Efficiency	58
Theme 4: International Best Practices Relevant to Research Infrastructures	58
<u>4.5 Theme 1: Drivers of Innovation and Sustainability</u>	59
<u>4.5.1 Scientific and Technical Capability</u>	59
<u>4.5.2 Regulatory Accreditation and Quality Systems</u>	60
<u>4.5.3 Collaborative Networks and Knowledge Ecosystems</u>	60
<u>4.5.4 Alignment with International Data and Research Standards</u>	61
<u>4.5.5 Strategic Alignment with National STI Priorities</u>	62
<u>4.5.6 Synthesis: Innovation as a Foundational Capability</u>	63
<u>4.6 Theme 2: Barriers to Adopting Sustainable Strategies</u>	63
<u>4.6.1 Infrastructure Deficiencies and Legacy-System Dependency</u>	63
<u>4.6.2 Funding Instability and Financial Constraints</u>	64
<u>4.6.3 Human-Capital Gaps and Operational Strain</u>	64
<u>4.6.4 Systemic Barriers: Policy, Regulatory Alignment and Institutional Fragmentation</u>	64
<u>4.6.5 Digital Maturity Constraints</u>	65
<u>4.6.6 Limited Commercialisation Pathways and Industry Engagement</u>	65
<u>4.6.7 Synthesis: Barriers as Interlocking Constraints</u>	65
<u>4.7 Theme 3: The Central Role of Digital Capabilities and Infrastructure</u>	65
<u>4.7.1 Scalable Digital Infrastructure</u>	66
<u>4.7.2 Operational Efficiency through Automation and Data Integrity</u>	67

4.7.3 Workforce Readiness and Digital-Capability Maturity	67
4.7.4 Strategic Alignment and Long-Term Digital Planning.....	67
4.7.5 Synthesis: Digital Capability as a Cross-Cutting Enabler	68
4.8 Theme 4: International Best Practices Relevant to Research Infrastructures	68
4.8.1 International Collaboration and Distributed Infrastructure Models.....	69
4.8.2 Open Science, FAIR Data, and Digital Interoperability	69
4.8.3 Governance Innovation and Stakeholder Integration	71
4.8.4 Dual-Use and Hybrid Service Models.....	71
4.8.5 Capacity-Building Systems and Global Competency Alignment	71
4.8.6 Synthesis: Implications for PCDDP.....	72
4.9 Theme 5: Strategic Recommendations for Integrating Innovation and Sustainability.....	72
4.9.1 Hybrid Revenue Model and Business-Model Diversification.....	73
4.9.2 Digital Transformation Roadmap and Data-Integrity Systems	74
4.9.3 Capacity and Talent Development	74
4.9.4 Governance Architecture and Stakeholder Ecosystem Development	74
4.9.5 Sustainability Metrics, Monitoring and Continuous Improvement	75
Integrated Conceptual View of Strategic Recommendations.....	75
4.10 Integrated Interpretation: Applying the RBV-OI-BMI Framework to the Empirical Findings	76
4.10.1 RBV Interpretation: Internal Capabilities and Their Constraints	76
4.10.1.3 Operational Capability Maturity	77
4.10.1.4 Interpretation: RBV Perspective on Capability Strength and Fragility	78
4.10.2 OI Interpretation: Collaboration as a Mechanism for Capability Extension.....	78
4.10.2.2 Outbound Knowledge Flows: Dissemination, Capacity Development and Scientific Visibility	79
4.10.2.3 Industry and Public Sector Linkages: Emerging but Constrained Engagement	79
4.10.2.4 Structural Dependencies and Absorptive Capacity Limitations	80
4.10.3 BMI Interpretation: Business Model Adaptation Under Structural Constraint.....	80
4.10.3.4 Digital Transformation as a Business Model Enabler	82
4.10.3.5 Interpretation.....	82
Interdependence Between RBV, OI, and BMI	83
4.12 Systemic Constraints as Generative Mechanisms.....	84
4.12.1 Funding Volatility	84
4.12.2 Procurement and Administrative Rigidity	84
4.12.3 Fragmentation in the National System of Innovation	85
4.12.4 Digital Immaturity.....	85
4.13 Emergent Sustainability Pathways.....	85
4.13.1 Systematic renewal of internal capabilities	85
4.13.2 Collaboration supported by conducive institutional and regulatory environments	85
4.13.3 Business model innovation enabled by operational flexibility	85
4.14 Implications for the PCDDP and the Broader Research Infrastructure Landscape	86
Implications for the PCDDP.....	86
4.14.2 Formalising Collaboration Governance.....	87
4.14.3 Accelerating Digitalisation as a Strategic Enabler	87
4.14.4 Repositioning the Business Model toward a Hybrid Logic.....	88
4.15 Implications for South Africa's National Research Infrastructure System.....	88

4.15.1 A National Lifecycle Investment Framework	88
4.15.2 Better Alignment Across Regulatory, Research and Innovation Agencies	88
4.15.3 National Digital Research Infrastructure	89
4.15.4 Expanded Human Capital Pipelines	89
4.16 Chapter Summary	90
5.1 Introduction	91
5.2 Synthesis of Findings in Relation to the Research Questions	92
RQ1: What are the key drivers of business-model innovation and sustainability within South African research infrastructures, particularly in the PCDDP?	92
RQ2: What barriers hinder the successful adoption and implementation of sustainable innovation strategies within the PCDDP?	92
RQ3: How do digital capabilities influence financial sustainability and operational efficiency in research infrastructures?	93
RQ4: Which international best practices can be adapted to improve sustainability and innovation within the PCDDP?	93
RQ5: What strategic recommendations can enhance the integration of business-model innovation and sustainability in South African research infrastructures?	94
5.3 Discussion of Findings Through the RBV-OI-BMI Lens	94
1. Extension of RBV, OI, and BMI Theory into Research Infrastructure Contexts	94
2. Conceptual Integration of RBV, OI, and BMI for Sustainable Research Infrastructures	95
3. Identification of Generative Mechanisms Limiting Business Model Innovation in Developing Systems	95
4. Empirical Validation of BMI in a Non-Commercial, High-Regulation Environment	96
5. Contribution to Sustainability Scholarship through the Lens of Scientific Infrastructure	96
6. Introduction of a Context-Specific Conceptual Framework for Developing Countries	96
5.4 Practical Implications	96
1. Strengthening Internal Capabilities through Structured Investment and Strategic Focus (RBV Implications)	97
2. Enhancing Collaborative Mechanisms and Ecosystem Engagement (OI Implications)	97
3. Reconfiguring Business Models for Hybrid Sustainability (BMI Implications)	98
4. Implications for National Policymakers and Funding Agencies	98
5.5 Limitations and Future Research	99
5.5.1 Limitations of the Study	99
5.5.2 Future Research Directions	100
<i>References</i>	102
<i>Appendix A: List of Documents Analysed in the Study</i>	133
A.1 Internal PCDDP and NWU Documentation	133
A.2 National Reports, Policy Documents, and Strategic Plans	133
A.3 International Policy and Benchmarking Documents (OECD and Related Sources)	133
A.4 Benchmarking Reports, Academic Literature, and Expert Sources	134
A.5 PCDDP Business Model Assessment Documents	134

LIST OF TABLES

<i>Table 1: Case Studies and examples of RIs in developing economies</i>	20
<i>Table 2: Thesis theme and keywords used in database search</i>	41
<i>Table 3: Types of Documents and Data Collected for the Study</i>	42
<i>Table 4: Thematic Analysis Process Overview (Adapted from Braun & Clarke, 2006; Naeem et al., 2023).</i>	55
<i>Table 5: Practical Implications Matrix</i>	99

LIST OF FIGURES

<i>Figure 1: Trends in governmental R&D budgets and (b) Trends in government financial support for business R&D according to OECD (2025).</i>	7
<i>Figure 2: The Preclinical Drug Development Platform (DSI/NWU PCDDP), based at North-West University (NWU) in South Africa focuses on preclinical research, drug and vaccine efficacy and toxicity testing in animals.</i>	9
<i>Figure 3: Integrated Theoretical Framework for Business Model Innovation and Sustainability in Research Infrastructures</i>	11
<i>Figure 4: RBV theory model illustrating the VRIN/VRIO attributes of organisational resources (modified from Mailani et al., 2024:3)</i>	22
<i>Figure 5: Research infrastructures conceptualised through the VRIN/VRIO lens, illustrating tangible and intangible capabilities relevant to scientific sustainability</i>	23
<i>Figure 6: Integrated conceptual framework illustrating the interaction between the Resource-Based View, Open Innovation, and Business Model Innovation in supporting sustainable research infrastructures.</i>	28
<i>Figure 7: Application of the integrated RBV–OI–BMI framework to the Preclinical Drug Development Platform (PCDDP), demonstrating how resource capabilities, external partnerships, and business model innovation pathways interact to enhance long-term sustainability and innovation performance.</i>	29
<i>Figure 8: Search strategy deployed in the study</i>	40
<i>Figure 9: Percentages of code variation calculated as a percentage under each main theme.</i> ..	56
<i>Figure 10: Sunburst diagram showing the overview of how the thematic codes were organised across the five core analytical areas guiding this study</i>	56

<i>Figure 11: Overview of the ELIXIR infrastructure, showing distributed nodes, shared data services, training networks and integrated community structures (modified from Harrow et al., 2021).</i>	61
<i>Figure 12: FAIR data model applied to life-science and preclinical research infrastructures (modified from Kemmer et al., 2023).</i>	62
<i>Figure 13: Digital capabilities underpin both operational efficiency and strategic sustainability, showing the interaction between day-to-day digital processes and long-term strategic systems.</i>	66
<i>Figure 14: Overview of the Preclinical Drug Development Platform (PCDDP) service ecosystem and infrastructure for 2026 (Overview of the ELIXIR infrastructure adapted to align conceptually with PCDDP's context)</i>	69
<i>Figure 15: Illustrative FAIR data lifecycle adapted for bioimaging and linked to GLP-aligned data-integrity requirements relevant to the PCDDP.</i>	70
<i>Figure 16: The PCDDP Business Model Transformation Pathway, illustrating the progression from a traditional regulatory testing model toward a sustainable and ultimately circular operating logic.</i>	73
<i>Figure 17: Conceptual model illustrating how the five strategic domains, innovation drivers, digital capabilities, sustainability mechanisms, international best practices, and barriers, interact to shape the PCDDP's sustainability trajectory.</i>	75

LIST OF ABBREVIATIONS

4IR	Fourth Industrial Revolution
AI	Artificial Intelligence
ATLAS.ti	Qualitative Data Analysis Software
BMI	Business Model Innovation
CSIR	Council for Scientific and Industrial Research (South Africa)
DSI	Department of Science and Innovation (South Africa)
EMBL	European Molecular Biology Laboratory
ESFRI	European Strategy Forum on Research Infrastructures
GLP	Good Laboratory Practice
NHREC	National Health Research Ethics Council (South Africa)
NSTF	National Science and Technology Forum
NSF	National Science Foundation (United States)
OECD	Organisation for Economic Co-operation and Development
PCDDP	Preclinical Drug Development Platform
RBV	Resource-Based View
RI	Research Infrastructures
SAHPRA	South African Health Products Regulatory Authority
SANReN	South African National Research Network
SDGs	Sustainable Development Goals
STI	Science, Technology, and Innovation
TBL	Triple Bottom Line
UK Biobank	United Kingdom Biobank

CHAPTER 1: INTRODUCTION AND OVERVIEW OF THE STUDY

1.1 Introduction

Research infrastructures are fundamental to scientific advancement, innovation, and socio-economic development. In South Africa, they act as critical enablers of knowledge production and technological progress, supporting national development priorities and global scientific collaborations (Mustapha and Ralphs, 2024; Daniels *et al.*, 2025). Despite their strategic importance, many South African research infrastructures struggle to achieve long-term sustainability and to embed innovation-driven growth. Persistent challenges include financial constraints, regulatory complexity, skills shortages, and fragmented approaches to integrating sustainability into innovation frameworks (OECD, 2025).

While sustainability strategies have been widely explored in corporate and manufacturing contexts, research infrastructures often lack clear frameworks for embedding business model innovation to support financial and operational sustainability (Van Nguyen, 2023; Mutua *et al.*, 2025). The Preclinical Drug Development Platform (PCDDP) offers an instructive case through which to explore these issues. Operating in a resource-constrained environment, the PCDDP is required to navigate the dual pressures of sustaining research excellence and maintaining financial viability (National Science and Technology Forum [NSTF], 2024). Although the platform has implemented several sustainability-oriented initiatives, there remains no structured, innovation-driven approach tailored to the specific realities of research infrastructures (Ramolobe & Khandanisa, 2024).

This study addresses this gap by investigating how business model innovation can enhance sustainability within South African research infrastructures, using the PCDDP as an exemplar. Through an in-depth qualitative case study, the research seeks to identify key enablers, barriers, and strategic mechanisms that can drive financial and operational sustainability while strengthening the competitive research capabilities of such infrastructures.

1.2 Problem Statement

Innovation is widely recognised as a critical driver of sustainability, competitiveness, and economic growth. However, within the South African research infrastructure landscape, the intersection between innovation, sustainability, and long-term business performance remains underexplored and fragmented (Azmat *et al.*, 2023). Despite policy efforts and targeted funding interventions, many research infrastructures continue to experience financial instability, regulatory burden, and uneven adoption of digital transformation strategies (NSTF, 2024). These constraints threaten their ability to deliver sustained research impact and to align with international standards for research infrastructure management.

As a leading biomedical research facility, the PCDDP is mandated to facilitate preclinical drug development and translational research. Nonetheless, it faces recurring funding volatility, operational inefficiencies, and challenges in meeting international benchmarks for sustainable research infrastructures (OECD, 2024). While some innovation and sustainability measures have been introduced, there is no comprehensive framework that systematically integrates business model innovation with sustainability objectives. Furthermore, there is limited empirical research on how South African research infrastructures can strategically adopt business model innovation to strengthen financial resilience, operational efficiency, and long-term impact (Sarpong *et al.*, 2023).

This study responds to these gaps by examining how innovation and sustainability can be embedded within the PCDDP's operational and financial model. By identifying key drivers and constraints in sustainable innovation, the research aims to generate actionable insights that inform managerial practice, policy design, and governance approaches for research infrastructures in South Africa.

1.3 Research Aim

The primary aim of this study was to examine how business model innovation can enhance the sustainability of South African research infrastructures, with a specific focus on the Preclinical Drug Development Platform (PCDDP). The study sought to evaluate the key factors influencing sustainability and innovation within research infrastructures, identify challenges that hinder effective implementation, and propose strategic recommendations to strengthen the long-term financial and operational viability of such facilities.

1.4 Research Objectives

To achieve the stated research aim, the study pursued the following objectives:

1. To identify the key drivers of business model innovation and sustainability within the PCDDP. This includes examining strategic resources, institutional capabilities, funding mechanisms, and collaborative processes that support innovation and long-term viability.
2. To examine the barriers that hinder the successful implementation of sustainable innovation strategies in South African research infrastructures. This involves analysing internal and external constraints, including financial challenges, regulatory complexities, skills shortages, and technological limitations.
3. To evaluate the role of digital transformation in enhancing financial sustainability and operational efficiency within the PCDDP. This includes assessing how digital

capabilities, data-driven processes, and emerging technologies support or constrain sustainable innovation.

4. To conduct a comparative analysis of international best practices in research infrastructure sustainability and assess their applicability to the South African context. This objective supports the development of a broader understanding of global sustainability frameworks and their relevance for local implementation.
5. To develop a strategic framework for embedding innovation and sustainability within research infrastructures to support long-term viability and research excellence.

1.5 Research Questions

The study was guided by the following research questions:

1. What are the key drivers of business model innovation and sustainability within South African research infrastructures, particularly in the context of the PCDDP?
2. What barriers hinder the successful adoption and implementation of sustainable innovation strategies within the PCDDP?
3. How do digital capabilities influence financial sustainability and operational efficiency in research infrastructures?
4. Which international best practices can be adapted to improve sustainability and innovation within the PCDDP?
5. What strategic recommendations can enhance the integration of business model innovation and sustainability in South African research infrastructures?

These questions collectively support the investigation of innovation and sustainability from organisational, technological, and strategic perspectives, enabling a coherent exploration aligned with the study's aim and objectives.

1.6 Scope of the Study

This study focused on innovation and sustainability within South African research infrastructures, with specific emphasis on the Preclinical Drug Development Platform (PCDDP). The research examined business model innovation, digital transformation, and financial sustainability within the context of preclinical drug development and research infrastructure management. A qualitative case study approach was adopted, drawing on document analysis and comparative benchmarking to assess the extent to which business model innovation can strengthen sustainability practices.

The study does not examine research infrastructures operating in unrelated sectors, such as energy or agriculture, and is delimited to health- and pharmaceutical-oriented research

infrastructures. The analysis centres on the period from 2011 to 2024, reflecting PCDDP's operational evolution and recent policy developments shaping the national research and innovation landscape. Although global best practices are incorporated for benchmarking, the emphasis remains on producing context-specific insights relevant to South Africa's research and development ecosystem.

By situating the study within this defined scope, the research ensures conceptual clarity and relevance, supporting the generation of both theoretical contributions and actionable managerial recommendations for enhancing sustainability and innovation in research infrastructures.

1.7 Theoretical Contribution

Although there is a substantial body of literature exploring business innovation, sustainability, and digital transformation, research infrastructures remain underrepresented within these discourses, particularly in developing economies. Existing models of business model innovation have largely been developed for corporate, manufacturing, and technology-intensive sectors, and do not fully account for the unique operational structures, funding dependencies, and regulatory environments of research infrastructures (Azmat *et al.*, 2023; Singh and Ru, 2023:28446).

This study contributes to the theoretical development of business model innovation and sustainability by applying these concepts to the context of research infrastructures. Through its focus on the Preclinical Drug Development Platform (PCDDP), the research extends the applicability of established theories to an institutional domain where business model innovation has been less systematically examined. The study demonstrates how innovation and sustainability frameworks can be adapted to institutions characterised by long-term funding horizons, public-private interdependencies, and the need to balance research excellence with operational viability.

The theoretical contribution is strengthened through the integration of three complementary frameworks:

- Resource-Based View (RBV) - which explains how unique tangible and intangible resources, including expertise, regulatory accreditation, and research capabilities, support sustainable advantage in research infrastructures (Kamardi *et al.*, 2022:775).
- Open Innovation Theory - which highlights the value of collaborative networks, industry partnerships, and knowledge-sharing arrangements in strengthening innovation capacity and financial sustainability (Arsanti *et al.*, 2024; Banga & Gaile-Sarkane, 2025; Saemaldaher & Emeagwali, 2025).
- Business Model Innovation (BMI) - which focuses on how organisations revise or redesign business models to create and capture value in ways that enhance long-term

sustainability (van Tonder *et al.*, 2023:944; Capurro *et al.*, 2024:49; Omidvar *et al.*, 2025).

By integrating these frameworks into a single analytical lens, the study contributes to a more holistic understanding of how research infrastructures can balance sustainability, collaborative innovation, and financial resilience. It refines existing theoretical models by incorporating context-specific factors relevant to developing economies, including regulatory constraints, public-sector funding cycles, and the evolving role of universities within national innovation systems.

1.8 Practical Contribution

This study offers several practical contributions for research infrastructure managers, policymakers, research institutions, and funding bodies responsible for ensuring the sustainability and effectiveness of scientific facilities. Research infrastructures globally are under increasing pressure to maintain financial viability while continuing to support scientific excellence (OECD, 2024). In the South African context, these pressures are compounded by funding constraints, skills shortages, and regulatory barriers that limit opportunities for innovation and revenue diversification (NSTF, 2024).

By identifying the key drivers of innovation and sustainability, the study provides evidence-based recommendations that can support more resilient and adaptive strategies within research infrastructures. Specifically, the research contributes:

- Strategic guidance for managers and directors of research infrastructures, enabling them to develop business models that integrate sustainability principles, diversify revenue streams, and build operational resilience.
- Insights for policymakers and research funders, supporting the design of regulatory frameworks and funding mechanisms that encourage collaborative partnerships, investment in digital capabilities, and long-term sustainability.
- Decision-making tools for research organisations, highlighting international best practices and illustrating how these can be adapted to the South African research environment.
- Practical strategies for leveraging digital capabilities, enabling research infrastructures to improve operational efficiency, strengthen financial sustainability, and enhance their scientific impact.

The study also proposes a structured sustainability framework to support the transition of research infrastructures such as the PCDDP from a predominantly research-focused model to a more financially robust, innovation-driven organisation. This includes guidance on engaging industry partners, pursuing new funding models, and embedding sustainability within everyday operational practices.

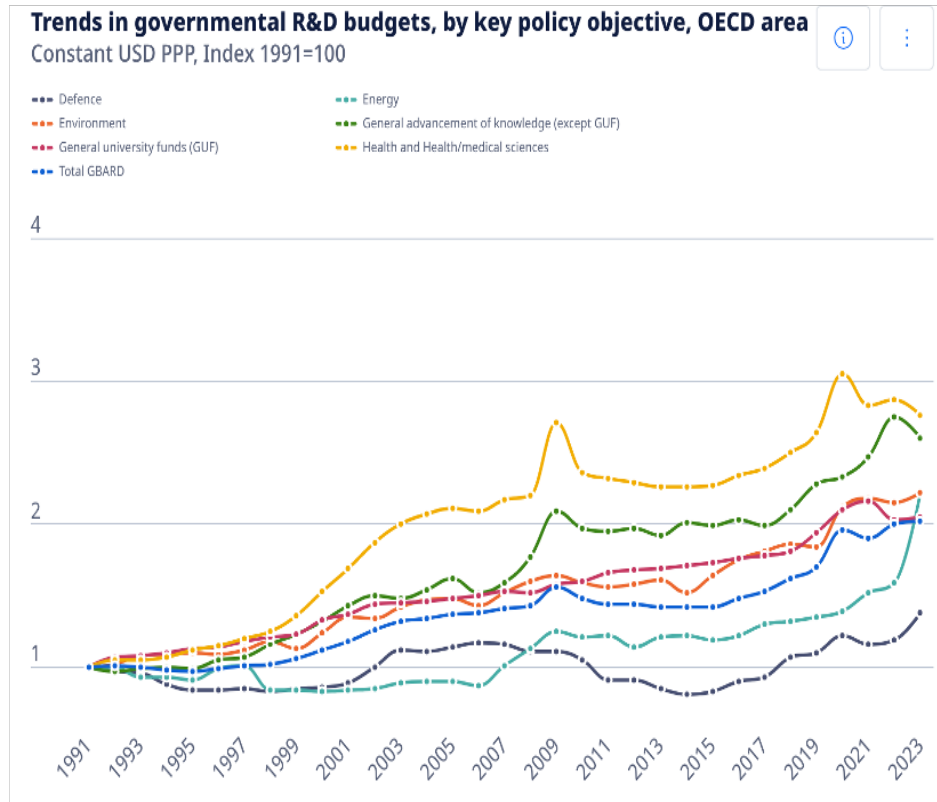
1.9 Innovation and Sustainability in Research Infrastructures

Research infrastructures (RIs) serve as essential enablers of scientific discovery, technological development, and socio-economic progress (OECD, 2025). Their long-term viability depends increasingly on the ability to integrate innovation with sustainable operational models, particularly in knowledge-driven economies where research excellence and resource efficiency must coexist (Fabre *et al.*, 2021). Globally, the interplay between innovation and sustainability is becoming central to how RIs operate, adapt, and deliver value to public and private stakeholders.

International research infrastructures are increasingly incorporating digitalisation, open innovation, and cross-sectoral collaboration into their strategies to strengthen long-term sustainability (Sarpong *et al.*, 2023). In South Africa, however, RIs often face significant barriers to implementing innovation-driven sustainability models. These include persistent funding constraints, uneven digital capability, regulatory complexity, and limited engagement with industry partners (Mustapha and Ralphs, 2024). As a result, many RIs struggle to achieve financial stability, despite their scientific and societal importance.

Understanding how RIs can integrate innovation and sustainability is therefore crucial. Business model innovation, the adoption of digital research tools, and the development of collaborative partnerships offer promising avenues for strengthening the sustainability of research infrastructures. The PCDDP provides a relevant context in which to explore these dynamics, given its mandate, operational constraints, and strategic role within South Africa's biomedical research ecosystem.

a)



b)

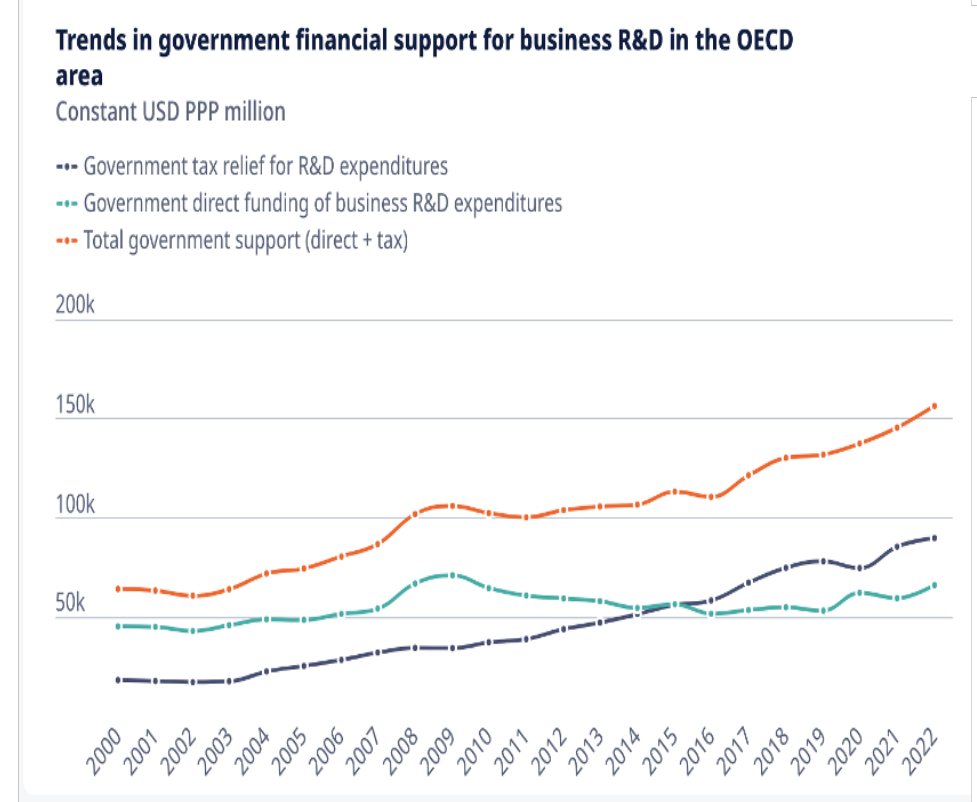


Figure 1: Trends in governmental R&D budgets and (b) Trends in government financial support for business R&D according to OECD (2025)

1.10 Historical Context and Global Benchmarking

The evolution of research infrastructures reflects broader historical shifts in scientific practice, technological development, and socio-economic priorities. Early research infrastructures of the late nineteenth and twentieth centuries were predominantly state-funded institutions focused on foundational scientific research and industrial innovation (Cass *et al.*, 2018). Over time, RIs have transformed into complex, multi-stakeholder entities linking universities, government agencies, industry partners, and global research networks.

In the era of the Fourth Industrial Revolution, digitalisation, artificial intelligence, and data-driven research methodologies are reshaping the expectations placed on research infrastructures (Rashid & Kausik, 2024). These technologies have become integral to sustaining competitive advantage, improving research efficiency, and enabling cross-disciplinary collaboration (Rust *et al.*, 2021). Contemporary RIs therefore operate within a global research ecosystem that values openness, interoperability, and long-term financial resilience.

Benchmarking international best practices reveals several sustainability-enhancing strategies adopted by leading research infrastructures:

- Long-term funding models, incorporating multi-year investment frameworks and public-private partnerships to reduce reliance on short-term grant cycles (OECD, 2024).
- Integration of digital and AI-enabled systems to support predictive analytics, laboratory automation, and data management (Zhai *et al.*, 2022).
- Global collaborative networks, enabling shared infrastructure use, talent mobility, and joint research programmes (Mustapha and Ralphs, 2024).
- Industry-academia partnerships, which strengthen technology transfer and generate new revenue streams for research facilities (Sarpong *et al.*, 2023).

These global practices provide valuable reference points for the South African research infrastructure environment. While contextual differences remain, several of these strategies can be adapted to improve the sustainability, operational resilience, and innovation performance of facilities such as the PCDDP.

1.11 Case Study Justification – PCDDP

The Preclinical Drug Development Platform (PCDDP) provides an appropriate and strategically relevant case study through which to examine business model innovation and sustainability in South African research infrastructures. As a nationally significant biomedical research facility, the PCDDP contributes directly to pharmaceutical innovation, drug discovery, and translational research (NSTF, 2024). Its operations span preclinical testing, regulatory compliance, and industry

collaboration, positioning it at the intersection of scientific research, commercial application, and public health (Figure 2).

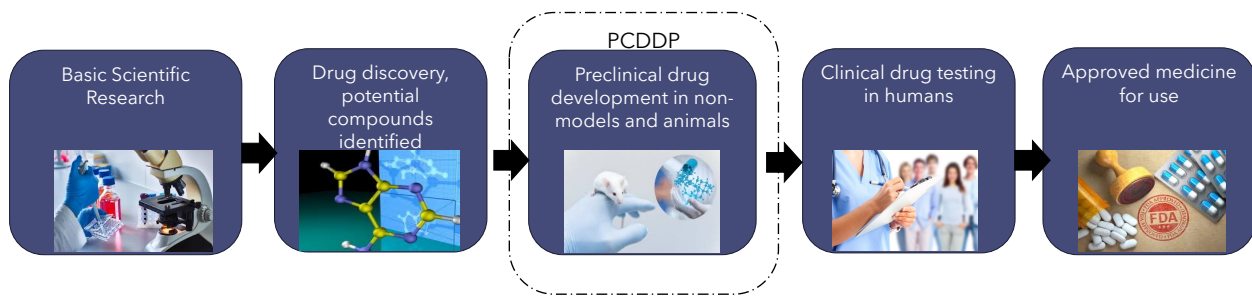


Figure 2: The Preclinical Drug Development Platform (PCDDP), based at North-West University (NWU) in South Africa focuses on preclinical research, drug and vaccine efficacy and toxicity testing in animals

The PCDDP offers a compelling case for several reasons. First, its strategic role in South Africa's research and innovation landscape highlights the importance of establishing sustainable operating models for research infrastructures that underpin national scientific capability. Second, the PCDDP faces financial, operational, and strategic challenges typical of South African research infrastructures operating in resource-constrained environments (Ramolobe & Khandanisa, 2024). These challenges include uncertainties in public funding, regulatory constraints, and pressures to diversify revenue streams.

Third, the PCDDP has initiated elements of innovation, including Good Laboratory Practice (GLP) accreditation, digital research tools, and collaborative projects with industry partners, which demonstrate the potential for business model innovation within research settings (OECD, 2024). However, these initiatives have yet to be integrated into a cohesive, sustainability-oriented business model.

Finally, insights derived from the PCDDP have broader applicability. As an exemplar research infrastructure facing common national challenges, the lessons emerging from this case can inform strategies for similar facilities across the South African science, technology, and innovation ecosystem (Van Nguyen, 2023). The case study therefore provides both analytical depth and practical relevance, strengthening the study's contribution to policy, management, and research infrastructure governance.

1.12 Conceptual and Theoretical Frameworks

This study is grounded in three complementary theoretical frameworks that together provide a multi-dimensional lens for analysing business model innovation and sustainability within research infrastructures. These frameworks, Resource-Based View (RBV), Open Innovation Theory, and Business Model Innovation (BMI), capture the organisational capabilities, collaborative structures,

and strategic mechanisms that shape sustainable performance (Peñarroya-Farell & Miralles, 2021; Wang *et al.*, 2025)

Resource-Based View (RBV)

The RBV posits that organisations achieve sustainable competitive advantage by leveraging valuable, rare, inimitable, and non-substitutable resources (Kamardi *et al.*, 2022:775). Within research infrastructures such as the PCDDP, these resources include state-of-the-art laboratory facilities, regulatory accreditations, domain expertise, and institutional reputation. RBV is a useful lens for understanding how internal capabilities, scientific, technical, and organisational, enable research infrastructures to sustain performance and innovate in competitive environments.

Open Innovation Theory

Chesbrough's Open Innovation Theory emphasises that organisations can enhance their innovation capacity by combining internal knowledge with external collaboration (Chesbrough & Bogers, 2014). For the PCDDP, open innovation manifests through partnerships with universities, biotechnology firms, regulatory authorities, and funding agencies. This framework highlights the importance of collaborative networks, knowledge exchange, and technology transfer in strengthening sustainability and expanding the impact of research infrastructures.

Business Model Innovation (BMI)

BMI focuses on how organisations design, adapt, or transform their business models to create and capture value in changing environments (Geissdoerfer *et al.*, 2018). Applied to research infrastructures, BMI involves developing new funding models, diversifying revenue streams, enhancing digital capability, and embedding sustainability principles into operational processes. BMI is particularly relevant for the PCDDP given its need to adapt to financial volatility and shifting demands within South Africa's research and innovation ecosystem.

Integration of the Three Frameworks

By integrating RBV, Open Innovation Theory, and BMI, this study adopts a holistic conceptual framework that accounts for the internal resources, external collaborations, and strategic processes shaping sustainability in research infrastructures. This concept is depicted in Figure 3 below.

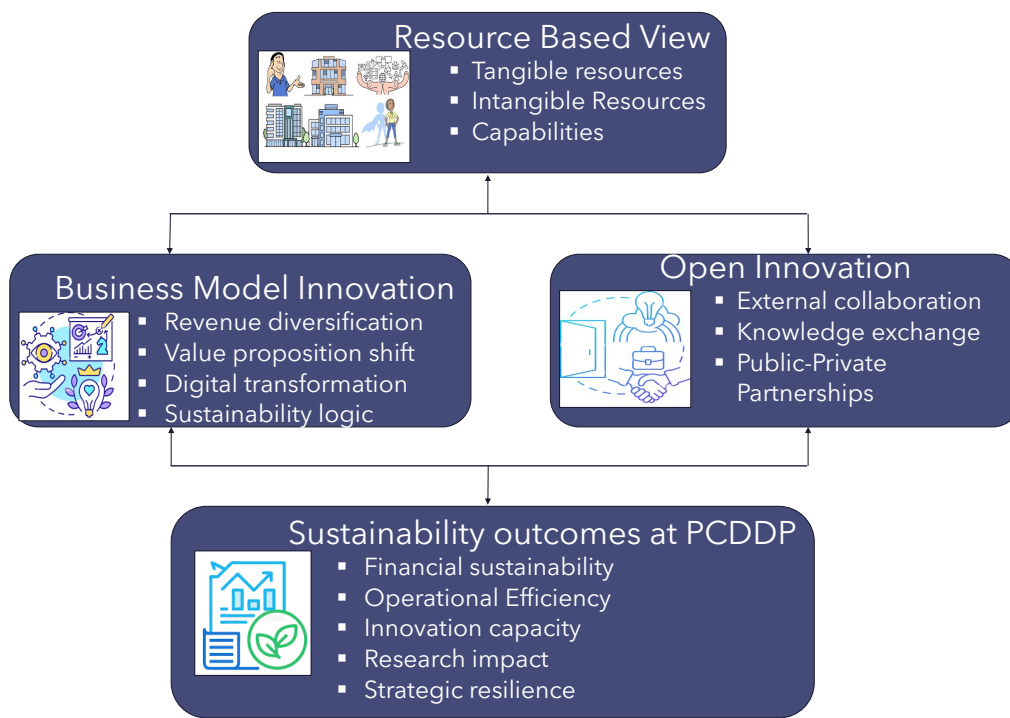


Figure 3: Integrated Theoretical Framework for Business Model Innovation and Sustainability in Research Infrastructures

This framework illustrates how internal capabilities (Resource-Based View), external collaboration mechanisms (Open Innovation Theory), and strategic business model adaptation (Business Model Innovation) collectively shape sustainability outcomes within research infrastructures such as the PCDDP. The model highlights the interdependent nature of organisational resources, collaborative networks, and innovation strategies in enhancing financial sustainability, operational efficiency, and research impact.

1.13 Definition of Key Concepts

A clear understanding of the key concepts underpinning this study is essential for establishing conceptual clarity and ensuring alignment with the theoretical frameworks applied. The following definitions provide the foundational terminology used throughout the research.

1.14. Innovation

Innovation refers to the development, application, or improvement of ideas, processes, or technologies that enhance organisational performance or research outcomes (Kogabayev & Maziliauskas, 2017; Duarte & Carvalho, 2025). In the context of research infrastructures, innovation includes scientific, technological, managerial, and collaborative advancements (Jürgens *et al.*, 2024; Ying *et al.*, 2025).

1.15 Sustainability

Sustainability denotes the ability of an organisation or infrastructure to maintain long-term operational, financial, and environmental viability (Elsawy & Marwan, 2023; Martins *et al.*, 2025). For research infrastructures, sustainability involves securing stable funding, ensuring efficient operations, and supporting ongoing scientific impact (Jürgens *et al.*, 2024).

Research Infrastructure

Research infrastructure encompasses the facilities, equipment, resources, and services that enable high-quality scientific research and innovation (OECD, 2024). This includes laboratories, research platforms, specialised staff, digital systems, and institutional frameworks that support scientific capability (D'Ippolito & Rüling, 2019:1282).

Digital Capabilities

Digital capabilities refer to an organisation's ability to deploy and leverage digital tools, information systems, and data analytics to improve research processes, operational efficiency, and decision-making (Qiao *et al.*, 2024; Van Hoang *et al.*, 2025). These capabilities include technical infrastructure, digital skills, and data management competencies.

Business Performance

Business performance relates to how effectively an organisation achieves its strategic, operational, and financial objectives (Tolici, 2021:165; Handoyo *et al.*, 2023; Mousa *et al.*, 2024). Within research infrastructures, business performance includes measures of financial sustainability, research output, operational efficiency, stakeholder engagement, and long-term competitive positioning (Jürgens *et al.*, 2024).

1.16 Research Design and Methodology Overview

This study employed a qualitative research design to explore how business model innovation can support the sustainability of research infrastructures in South Africa, with the Preclinical Drug Development Platform (PCDDP) serving as the primary case. A qualitative approach was appropriate given the exploratory nature of the research and the need to gain an in-depth understanding of organisational processes, strategic responses, and contextual factors shaping innovation and sustainability within research infrastructures (Rashid *et al.*, 2019; Nandhlal *et al.*, 2025:52).

The study was guided by a critical realist perspective, which acknowledges that observable organisational practices are influenced by deeper structural and contextual mechanisms (Stutchbury, 2021:113; Rao *et al.*, 2025:803). This paradigm supported a nuanced examination of the institutional, managerial, and systemic factors that enable or constrain business model

innovation. An abductive reasoning approach complemented this paradigm by allowing iterative movement between empirical observations and the theoretical frameworks underpinning the study (Aljehani *et al.*, 2024; Wang *et al.*, 2024; Gassol, 2025).

Data were generated primarily through document analysis and comparative benchmarking. These methods involved the systematic review of strategic plans, annual reports, policy documents, institutional performance reviews, and publicly available records relevant to the PCDDP and selected local and international research infrastructures. Together, these sources provided rich contextual evidence from which themes, patterns, and strategic insights were developed.

The detailed methodological procedures, including sampling logic, coding processes, data analysis techniques, validity measures, and ethical considerations, are presented in full in Chapter 3.

Limitations and Delimitations

As with all qualitative case study research, this study is subject to certain limitations and delimitations that define its scope and influence the interpretation of findings.

Limitations

The primary limitation relates to the single-case study design, which focuses exclusively on the Preclinical Drug Development Platform (PCDDP). While this approach provides rich, context-specific insight, it limits the extent to which findings can be generalised across all South African research infrastructures. To mitigate this, the study incorporates comparative benchmarking to enhance the relevance of insights beyond the focal case. A second limitation concerns the availability and completeness of documentary data.

The study relied on organisational records, strategic documents, and policy reports, which may vary in detail and transparency. Differences in the accessibility of certain internal documents could influence the depth of analysis in specific thematic areas. To strengthen validity, the study draws on multiple document types and triangulates insights across diverse sources.

A further limitation arises from the interpretative nature of qualitative thematic analysis, which carries the risk of subjectivity. Although structured coding procedures were applied during the full analysis (detailed in Chapter 3), researcher interpretation remains a potential source of bias. Reflexive practices and cross-checking of coded themes were used to enhance credibility.

Delimitations

The study is deliberately delimited to research infrastructures operating within the science, technology, and innovation domain, with a focus on biomedical and pharmaceutical research. Research infrastructures in unrelated sectors such as agriculture or energy fall outside the scope of inquiry. The research examines strategic developments, sustainability practices, and innovation activities within the timeframe 2020–2024, reflecting a period of operational transformation at the PCDDP and significant policy developments in the national research system. Earlier historical developments are referenced only where necessary for context.

Geographically, the study concentrates on the South African research ecosystem, with international cases used solely for benchmarking rather than primary data collection. The study also excludes technical evaluations of laboratory outputs and focuses instead on managerial, organisational, and strategic dimensions of sustainability and business model innovation.

These limitations and delimitations ensure that the research remains focused, methodologically coherent, and aligned with its aim of exploring sustainable innovation strategies within South African research infrastructures.

1.17 Dissertation Structure

This mini-dissertation is structured to support both rigorous examination and the development of publishable outputs. The document is organised into five chapters, each contributing to a coherent examination of business model innovation and sustainability within South African research infrastructures. At present, Chapter 2 is written in article format suitable for journal submission, while the remaining chapters follow a traditional dissertation structure and provide the empirical and integrative foundation for a second future article.

Chapter 1 introduces the study by outlining the background, problem statement, research aim, objectives, research questions, and theoretical framing. It also provides a high-level overview of the research design, key definitions, study boundaries, and the structure of the dissertation.

Chapter 2 presents Article 1, a conceptual and theoretical paper that examines the foundations of business model innovation, sustainability, and digital transformation within research infrastructures. It integrates the Resource-Based View, Open Innovation Theory, and Business Model Innovation to propose a conceptual framework applicable to research infrastructures such as the PCDDP.

Chapter 3 provides the full research methodology for the empirical component of the study. It outlines the research paradigm, design, data collection methods, data analysis procedures, trustworthiness strategies, and ethical considerations guiding the investigation. Chapter 4 reports the empirical findings of the case study. The chapter synthesises the thematic results, comparative benchmarking insights, and their implications for business model innovation and sustainability at the PCDDP. Chapter 5 provides an integrative conclusion, drawing together theoretical and

empirical insights from the preceding chapters. It outlines the study's contributions, implications for policy and practice, and recommendations for strengthening sustainability within South African research infrastructures. Directions for future research are also identified.

1.18 Conclusion

This chapter has introduced the study by outlining the strategic importance of research infrastructures within South Africa's national innovation system. It highlighted the sustainability challenges faced by these infrastructures, particularly in resource-constrained environments, and identified a gap in understanding how business model innovation can be leveraged to enhance long-term financial and operational viability. The PCDDP was presented as an exemplar case through which these issues can be explored.

The problem statement emphasised the limited integration of innovation and sustainability frameworks within South African research infrastructures and the need for a structured approach to embedding business model innovation. The chapter then articulated the research aim, objectives, and questions, which collectively guide the investigation of innovation drivers, barriers, digital capabilities, international best practices, and strategic recommendations.

A conceptual and theoretical foundation was established through the integration of the Resource-Based View, Open Innovation Theory, and Business Model Innovation, providing a multi-dimensional framework for analysing the PCDDP. Key concepts central to the study were defined to ensure conceptual clarity. A brief research design overview outlined the qualitative, abductive, single-case study approach and the use of document analysis and comparative benchmarking as primary data sources. The chapter also clarified the study's limitations and delimitations and presented the overall structure of the mini-dissertation, which combines an article-based theoretical chapter with conventional empirical and integrative chapters. This structure supports both scholarly contribution and practical relevance. The next chapter presents the conceptual and theoretical foundations of business model innovation and sustainability in research infrastructures.

CHAPTER 2: BUSINESS MODEL INNOVATION FOR RESEARCH INFRASTRUCTURES IN DEVELOPING ECONOMIES: INTEGRATING RESOURCE-BASED VIEW, OPEN INNOVATION, AND BUSINESS MODEL INNOVATION

This article was prepared for the African Journal of Science, Technology, Innovation and Development (AJSTID), a DHET-accredited journal.

Abstract

Research infrastructures (RIs) are essential components of national science, technology, and innovation systems, yet their long-term sustainability remains a persistent challenge, particularly in developing economies. Existing business model theories, largely developed for corporate and technology-intensive sectors, offer valuable insights into value creation and organisational performance but have not been sufficiently adapted to the unique governance, funding, and capability structures of RIs. This article addresses this conceptual gap by examining how the Resource-Based View (RBV), Open Innovation (OI), and Business Model Innovation (BMI) can be integrated to support sustainable business model development within RIs. Through a critical analysis of the literature, the article demonstrates that RBV highlights the strategic role of tangible and intangible RI resources, OI underscores the importance of collaborative knowledge flows, and BMI provides the mechanism through which internal capabilities and external partnerships can be transformed into sustainable operational models. The article proposes a conceptual framework that synthesises these lenses and is tailored to the realities of research infrastructures in developing economies, characterised by hybrid funding models, capability constraints, and public-good mandates. The framework offers theoretical and practical insights for RI managers, policymakers, and funders seeking to enhance sustainability, financial resilience, and innovation-driven growth. This conceptual foundation provides the basis for the empirical analysis presented in the subsequent article in this dissertation.

Keywords

Research infrastructures; business model innovation; Resource-Based View; open innovation; sustainability; developing economies; innovation ecosystems; public research organisations.

Introduction

Research infrastructures (RIs) constitute an essential pillar of contemporary innovation systems, enabling scientific discovery, technological progress, and socio-economic development (Zakaria *et al.*, 2021:1; Jürgens *et al.*, 2024). They provide the specialised facilities, expertise, and collaborative platforms required for high-quality research, while supporting national development priorities through knowledge production, capacity building, and research translation. In both advanced and developing economies, RIs now play a strategic role in fields such as biomedical research, clean technologies, digital transformation, and data-intensive science (Zakaria *et al.*, 2021; Jürgens *et al.*, 2024; OECD, 2025). Despite their importance, the long-term sustainability of RIs remains a persistent concern. Rising operational costs, skills shortages, regulatory complexity, and intensified competition for research funding place significant pressure on their ability to remain viable and globally competitive (Dañobeitia *et al.*, 2023; NSTF, 2024).

These constraints are more pronounced in developing economies, where RIs frequently operate within volatile funding environments characterised by dependence on public allocations, limited private-sector engagement, and constrained institutional capabilities (Klincewicz & Zaei, 2025; Ramadhan, 2025:29). Traditional governance and funding models have proved inadequate for ensuring long-term sustainability, particularly as RIs are increasingly expected to demonstrate societal impact, support collaborative knowledge production, and contribute to industrial and innovation policy objectives (Jürgens *et al.*, 2024; Gassol, 2025; Shabbir *et al.*, 2025). This has prompted growing interest in more adaptive, innovation-oriented approaches to RI management that strengthen financial resilience while maintaining scientific excellence and public value (Ramoutar-Prieschl & Hachigonta, 2020; Gassol, 2025).

Although extensive literature examines business models, innovation processes, and organisational strategy in commercial and technology-intensive sectors (Lei *et al.*, 2025; Li, 2025; Spieth *et al.*, 2025:166), their application to RIs remains limited. Research infrastructures differ from private firms in fundamental ways: they generate both public and private value; operate under stringent scientific and regulatory requirements; rely on multi-stakeholder governance structures; and pursue missions extending beyond financial performance to include scientific integrity, capacity development, and societal benefit (Smits *et al.*, 2020; Jürgens *et al.*, 2024). As a result, conventional business model frameworks do not fully capture the hybrid value structures, lifecycle financing needs, or collaborative dependencies inherent in RI environments. This gap limits the ability of RIs, particularly in resource-constrained settings, to innovate strategically, diversify revenue streams, and sustain their core capabilities.

This article addresses this conceptual gap by examining how the Resource-Based View (RBV), Open Innovation (OI), and Business Model Innovation (BMI) can be integrated to enhance theoretical understanding of sustainable business models for RIs. RBV provides insight into how distinctive organisational resources and capabilities shape long-term advantage; OI highlights the importance of collaborative knowledge flows and external partnerships; and BMI offers a mechanism through which internal capabilities and external opportunities can be recombined to generate sustainable operational models. Together, these perspectives offer a complementary and analytically rich foundation for reconceptualising RI sustainability, particularly in developing economies.

The purpose of this conceptual article is threefold:

1. to examine the applicability of established business model theories to the RI context;
2. to identify the limitations of these frameworks when applied to mission-driven scientific infrastructures; and
3. to propose an integrated conceptual framework that synthesises RBV, OI, and BMI as a foundation for sustainable business model design in RIs.

In doing so, the article contributes to an emerging body of scholarship that positions RIs not only as scientific assets but as organisational actors embedded within broader innovation ecosystems.

Literature Review

Research Infrastructures

RIs constitute foundational assets within national science and innovation systems. They encompass specialised facilities, advanced equipment, data platforms, and technical expertise that enable high-quality scientific research and support the development of skilled human capital (Zakaria *et al.*, 2021; Reilly *et al.*, 2023; Xing *et al.*, 2025). Their role extends beyond physical infrastructure to long-term scientific missions, regulatory compliance, interdisciplinary collaboration, and the formation of innovation ecosystems (Xing *et al.*, 2025). In developing economies, RIs additionally address capability deficits, facilitate international partnerships, and contribute to regional competitiveness (NSTF, 2024; Reilly *et al.*, 2023; Xing *et al.*, 2025).

Unlike commercial enterprises, RIs pursue hybrid missions that combine public-good outputs such as knowledge production, training, datasets, and scientific credibility, with selected market-facing services (Zhaksylyk *et al.*, 2023; Jürgens *et al.*, 2024). Their sustainability is shaped by funding stability, governance quality, scientific capability, and adherence to accreditation standards (OECD, 2025). Persistent challenges in African contexts include funding volatility, skills shortages, fragmented institutional coordination, and outdated infrastructure, all of which constrain long-term operational viability (Ramoutar-Prieschl & Hachigonta, 2020). These characteristics distinguish RIs

from private-sector organisations and highlight the need for appropriately adapted business model approaches.

Business Models and Business Model Innovation

Business models describe how organisations create, deliver, and capture value (Teece, 2018). Early definitions focused on revenue logic, value chains, and competitive positioning, whereas more contemporary perspectives emphasise integrated value systems, stakeholder relationships, and the alignment between resources, capabilities, and strategic choices (Ritter & Lettl, 2018; Teece, 2018; D'Oria *et al.*, 2021). BMI entails reconfiguring value propositions, value creation processes, and value capture mechanisms to enhance organisational resilience, performance, or sustainability (Andreini *et al.*, 2022; Bashir *et al.*, 2025).

Applying conventional business model logic to RIs is complex, as RIs do not participate in competitive markets in the same way as firms. Their mandates prioritise scientific integrity, public value, and societal impact, while income diversification is often constrained by regulatory requirements and grant dependence (Zhaksylyk *et al.*, 2023; Jürgens *et al.*, 2024). Nonetheless, the principles of BMI, such as redesigning operational systems, forming new partnership structures, and integrating digital capabilities (Andreini *et al.*, 2022; Bashir *et al.*, 2025), are increasingly relevant to RIs seeking to enhance long-term sustainability.

Sustainable Business Models

Sustainable business models extend traditional business model thinking by embedding environmental, social, and long-term economic considerations in value creation (Nosratabadi *et al.*, 2019; Knudson, 2023:101). They emphasise multi-stakeholder engagement and alignment with broader sustainability commitments, including responsible resource use and contributions to societal well-being (Rathobei *et al.*, 2024:3687; Wanner & Miljand, 2025).

Although this literature provides useful conceptual tools, its direct applicability to RIs remains limited. Many sustainability models assume commercial incentives and measurable market-based value, whereas RIs typically generate scientific outputs whose value may be indirect, diffuse, or non-market in nature (Jiang *et al.*, 2023; OECD, 2019; 2025). Impact evaluation in RIs is inherently complex, as assessments must capture scientific influence, capacity development, policy contributions, and broader socio-economic effects (OECD, 2019; Kolar *et al.*, 2003; Jürgens *et al.*, 2024). Sustainable business model principles therefore require adaptation to the scientific and regulatory realities of RIs. Table 1 shows examples of RIs in developing economies and key lessons for business models.

Table 1: Case Studies and examples of RIs in developing economies

Case study	Key Lessons for Business Models and RIs
Several test facilities in sub-Saharan Africa working toward OECD GLP compliance, supported by the Innovative Vector Control Consortium (IVCC) plus partners for insecticide-testing.	Infrastructure and equipment limitations, shortages of skilled human resources, the cost and complexity of implementing new Quality Management Systems (QMS) and Standard operating procedures, and difficulties in coordinating with external regulatory systems (Small, 2022)
A partner facility of IVCC, Institut de Recherche en Science de la Santé (IRSS) facility achieved full GLP certification after years of structured support in Burkina Faso	Challenges faced included infrastructure development, limited regional expertise and capacity for specialized roles, and the need to create financial sustainability and long-term training initiatives to meet rigorous GLP standards and demand for its services. These challenges were overcome through sustained, structured support from IVCC, which provided access to external specialists, funding for improvements, and a long-term strategy to develop a certified facility capable of conducting high-quality malaria and neglected tropical disease research (Begg <i>et al.</i> , 2021).
Initiative to unlock R&D funding via multi-stakeholder collaboration through Science for Africa Foundation or Grand Challenges Africa	Science for Africa Foundation and Grand Challenges Africa faced challenges in adopting sustainable business models for R&D funding due to insufficient domestic funding, reliance on foreign donor priorities, the difficulty of navigating between concept and market, a lack of digital infrastructure, and the need to build African research capacity (Mugwagwa <i>et al.</i> , 2019).
Sustaining Research Infrastructures in Africa via PPPs (public-private partnership) models to build or maintain research infrastructure in Africa.	PPPs can be a mechanism to bring private capital, expertise, or management practices in, while ensuring public research missions. But these need clear agreements, governance, and often require support for operating costs, not just capital expenditure (Shen <i>et al.</i>, 2006; Liu <i>et al.</i>, 2026:31). In several developing countries, PPPs involving universities or tertiary institutions have been used to bring

	in private capital and expertise to build or upgrade research or academic infrastructure. For example, Yaba College of Technology in Nigeria used PPPs to support internally generated revenue and maintain academic infrastructure (Toriola-Coker <i>et al.</i>, 2022:4122). In Kenya, public universities in Nairobi have used PPPs for procurement of institutional infrastructure, with success depending heavily on governance, legal frameworks, and clarity in agreements (Thiga, 2025:10). In South Africa, analyses of PPPs suggest that capital expenditure, operating and maintenance costs, challenges with research funding, lack of support from policymakers and poor governance, and the lack of trust and cooperation between public and private players (NSTF, 2024; Ramolobe & Khandanisa, 2024).
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Resource-Based View (RBV)

The Resource-Based View (RBV) offers an established theoretical lens for analysing organisational advantage. It posits that unique bundles of tangible and intangible resources, when valuable, rare, inimitable, and organisationally embedded, form the basis of sustained performance (Mailani *et al.*, 2024:1). Figure 4 below illustrates the VRIN/VRIO logic central to RBV.

In the context of RIs, RBV provides a structured means of analysing distinctive resource profiles (Bhandari *et al.*, 2020:363). Tangible resources include specialised laboratories, advanced scientific equipment, accredited animal facilities, and digital research platforms (Huerkamp *et al.*, 2018; Gangwal & Lavecchia, 2025). Intangible resources comprise scientific expertise, long-term datasets, institutional reputation, governance structures, and regulatory trust (Navarro-García *et al.*, 2024). These resources reflect VRIN/VRIO characteristics to varying degrees and may contribute to strategic advantage within the broader research ecosystem (Yang *et al.*, 2022; Mailani *et al.*, 2024:1).

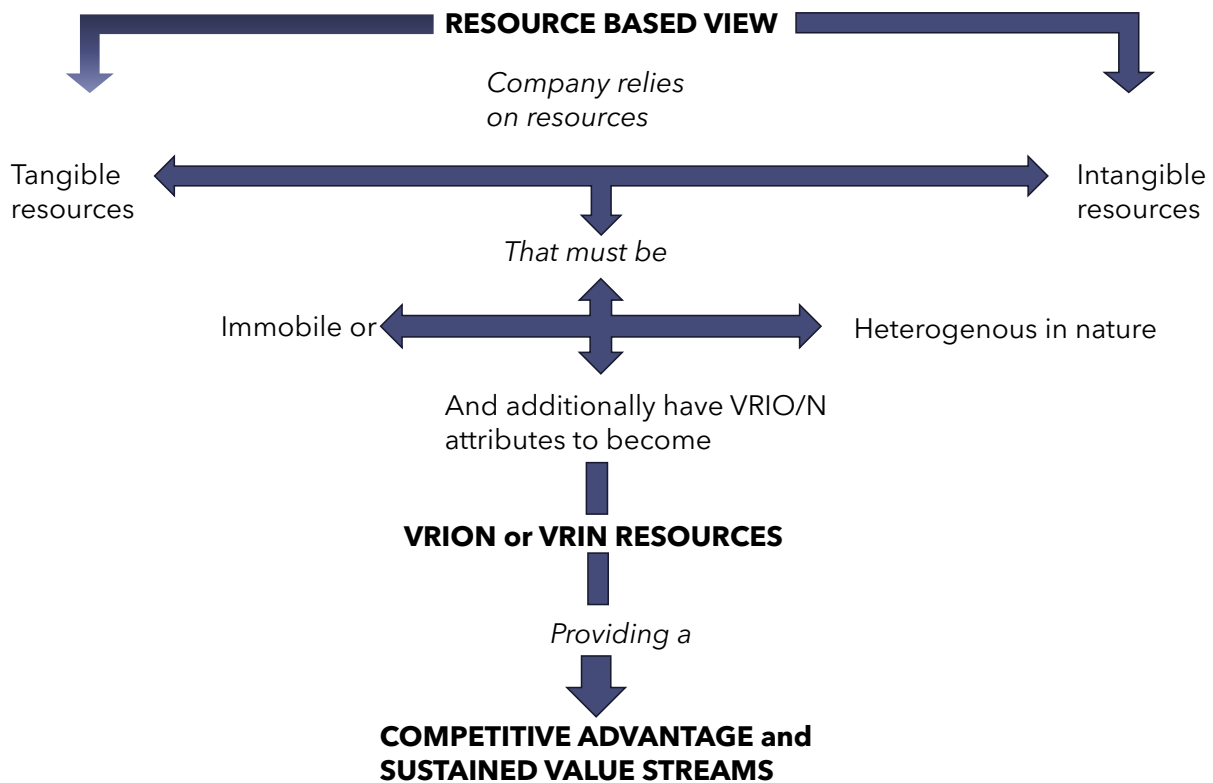


Figure 4:RBV theory model illustrating the VRIN/VRIO attributes of organisational resources (modified from Mailani *et al.*, 2024:3)

However, RBV alone is insufficient for explaining RI sustainability. Internal capabilities do not guarantee long-term viability without strong external partnerships, diversified funding models, and adaptive organisational processes (Chen & Yu, 2022; Mutambik, 2024; Zungu *et al.*, 2025:1847). In developing economies, resource accumulation and renewal are further constrained by systemic limitations (Falcone, 2023; Wangg *et al.*, 2023). RBV therefore provides an essential but partial perspective that requires integration with complementary theoretical frameworks (Mailani *et al.*, 2024:1-3). Figure 5 illustrates RBV adapted to the RI context.

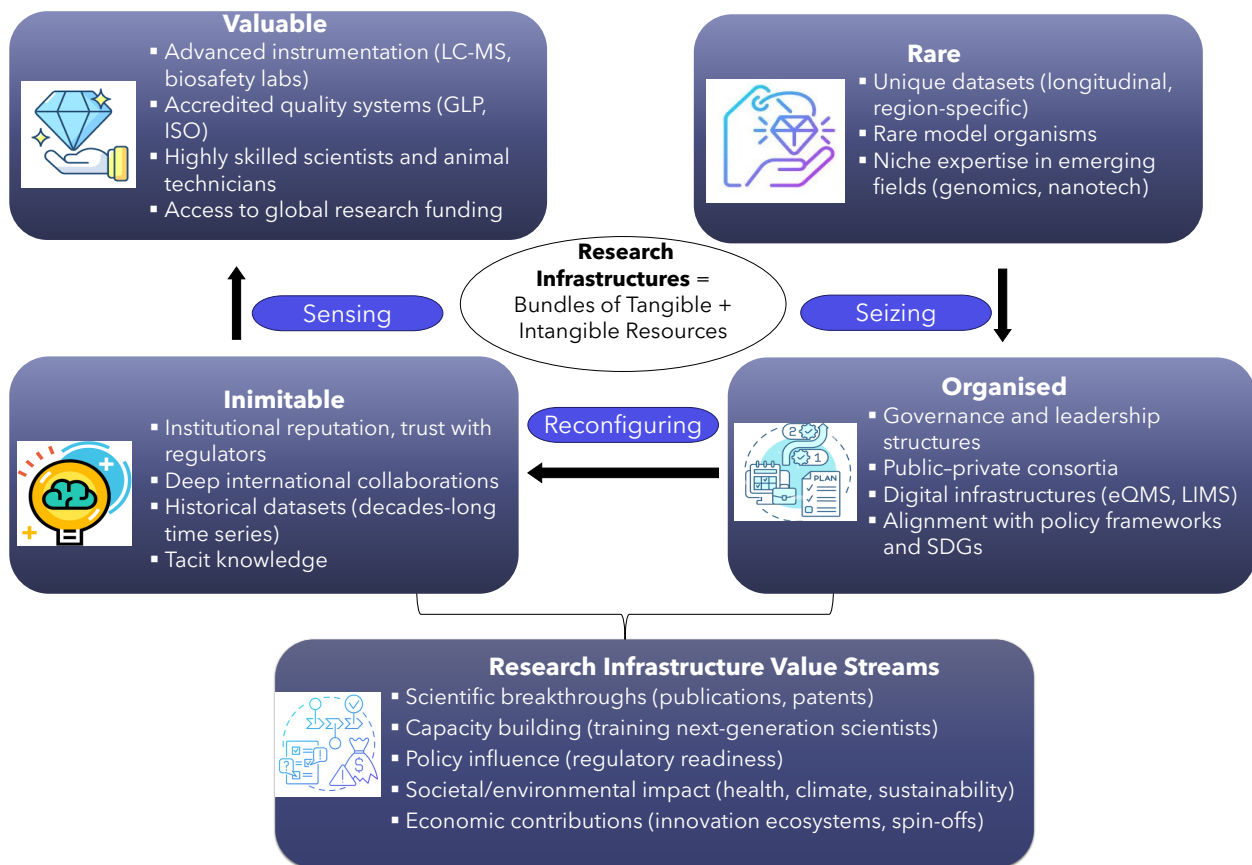


Figure 5: Research infrastructures conceptualised through the VRIN/VRIO lens, illustrating tangible and intangible capabilities relevant to scientific sustainability

Open Innovation (OI)

Open Innovation (OI) highlights purposive knowledge flows across organisational boundaries, enabling collaboration, co-development, and shared value creation (Arsanti *et al.*, 2024; Gionfriddo & Piccaluga, 2025:137). RIs are inherently open systems that they rely on partnerships with universities, industry, government agencies, non-profit organisations, and international networks to access expertise, technologies, and financial resources (Awasthy *et al.*, 2020:50; Wang *et al.*, 2023:357; Sotirofski, 2024). Their outputs, including data platforms, publications, training, and specialised services, contribute directly to national and global knowledge ecosystems, making OI particularly relevant for understanding RI operations (Jürgens *et al.*, 2024).

Inbound OI enables RIs to draw on external scientific expertise, emerging methodologies, advanced technologies, and global regulatory standards (Leitão *et al.*, 2020). Outbound OI includes dissemination of research outputs, shared data resources, policy contributions, capacity development, and technology transfer activities. In resource-constrained contexts such as South Africa, OI helps mitigate capability gaps by linking RIs to distributed knowledge networks (Leitão *et al.*, 2020; Kruger & Steyn, 2024).

Notwithstanding its value, OI adoption faces contextual constraints. Regulatory rigidity limited intellectual property infrastructure, digital maturity gaps, and trust deficits between academia and industry restrict the breadth of collaboration (Ahmed *et al.*, 2022; Rossoni *et al.*, 2023). Consequently, while OI is central to RI functioning, it provides only a partial foundation for understanding sustainability, reinforcing the need for an integrated theoretical approach.

Theoretical Integration: RBV, OI and BMI for Research Infrastructures

The sustainability of research infrastructures cannot be explained adequately through any single theoretical lens. Each of the three frameworks reviewed, RBV, OI, and BMI, provides valuable insights, but each remains incomplete when applied in isolation to research infrastructures, which operate under hybrid mandates, resource constraints, and complex governance demands (Chesbrough & Tucci, 2020; Jürgens *et al.*, 2024). An integrated approach is therefore necessary to understand how RIs can strengthen long-term viability, enhance innovation performance, and adapt to evolving scientific and funding environments.

Why RBV Alone Is Insufficient

RBV highlights the strategic importance of the tangible and intangible resources that underpin an RI's value proposition, including specialised equipment, scientific expertise, accreditation, data assets, and institutional reputation (Mailani *et al.*, 2024:1-2). These resources influence an RI's ability to deliver high-quality research, maintain compliance, and attract collaborators, funders, and talent (Hamra *et al.*, 2019; Kamenetzky & Hinrichs-Krapels, 2020).

However, RBV presumes that organisations can leverage and renew internal resources with relative independence (D'Oria *et al.*, 2021:1383). This assumption does not hold for RIs in developing economies, where structural constraints such as limited capital, skills shortages, rigid procurement systems, and dependence on public funding limit resource renewal (Fourie & Malan, 2020). Moreover, scientific progress depends fundamentally on collaboration, meaning that RI resources cannot be fully exploited without strong external engagement (Jürgens *et al.*, 2024). RBV therefore provides an essential but partial explanation of RI sustainability and must be complemented by theories that account for knowledge flows and collaborative ecosystems.

Why OI Alone Is Insufficient

Open Innovation situates RIs within broader knowledge networks and underscores the role of inbound and outbound collaboration in expanding their scientific and operational capabilities (Arsanti *et al.*, 2024; Sithipolvanichgul *et al.*, 2025:2745). RIs regularly rely on external scientific partners, donors, industry actors, and government agencies to mobilise expertise, reduce duplication, and enhance scientific relevance (Boulton, 2022:832; Puyvallée *et al.*, 2024:25; Mayor *et al.*, 2025).

Yet OI assumes that organisations possess sufficient absorptive capacity to integrate and apply external knowledge effectively (Abourobkbah *et al.*, 2023). Many RIs in developing economies face capability constraints, such as insufficient digital infrastructure, limited technical skills, or weak managerial processes that restrict their ability to operationalise the benefits of collaboration (Mirzaye & Mohiuddin, 2025). Additionally, accreditation requirements, biosafety standards, and regulatory oversight introduce limits on organisational openness (Gillum *et al.*, 2024). OI therefore provides a valuable but incomplete lens without an understanding of internal capabilities and strategic mechanisms, which RBV and BMI supply.

Why BMI Is the Integrative Mechanism

Business Model Innovation provides the operational mechanism that connects internal capabilities (RBV) with external collaborative opportunities (OI) (Kero & Bogale, 2023; Ademi *et al.*, 2025:19). Through BMI, RIs can redesign value creation processes, partnership structures, and revenue models to enhance sustainability. Within RIs, BMI may involve:

- diversifying revenue through contract research, specialised testing services, or capacity-building programmes (Pittz *et al.*, 2024:53-55)
- adopting digital platforms and quality management systems to improve efficiency and global connectivity (Li *et al.*, 2024:1)
- restructuring governance to support collaborative and transparent decision-making (Mueller-Saegebrecht, & Walter, 2025:407)
- aligning scientific missions with funder expectations and societal needs (Trotter & Brophy, 2022)
- refining organisational processes to ensure regulatory and accreditation readiness (Steel *et al.*, 2025)

BMI thus enables RIs to translate resources and collaborations into sustainable operating models, making it a necessary complement to RBV and OI.

Integrated Argument: RBV, OI and BMI as a Composite Lens

Synthesised, the three frameworks offer a coherent explanation of RI sustainability:

- RBV identifies the internal sources of scientific and organisational strength.
- OI positions the RI within collaborative knowledge networks that expand and extend these strengths.
- BMI orchestrates the redesign of the business model to integrate internal capabilities and external partnerships into sustainable outcomes.

Together, these perspectives provide a comprehensive theoretical foundation for understanding how RIs in developing economies can transition from resource dependence and funding vulnerability toward more adaptive, resilient, and innovation-driven models.

This integration forms the basis of the conceptual framework presented in Section 7, which maps the interaction between the three theoretical pillars and explains how they combine to support sustainable research infrastructures.

Conceptual Framework: A Business Model Innovation Approach for Research Infrastructures

This section presents the integrated conceptual framework developed from the synthesis of the RBV, OI and BMI. The purpose of the framework is to provide a theoretically coherent and context-sensitive model for understanding how research infrastructures in developing economies can strengthen their sustainability, enhance innovation performance, and improve long-term organisational resilience.

The framework draws directly on the thematic insights developed in the preceding sections and is visually represented in the figures (Figures 4, 5 and 6).

Logic of the Framework

The conceptual framework rests on the premise that sustainability in research infrastructures emerges from the dynamic interaction between internal capabilities, external knowledge flows, and strategic business model redesign. Each theoretical pillar plays a specific role:

- RBV identifies the tangible and intangible resources that form the core capabilities of an RI and determine its potential for scientific credibility and differentiation.
- OI positions the RI within a broader collaborative ecosystem, highlighting how inbound and outbound knowledge flows extend, update, or complement internal capabilities.
- BMI serves as the mechanism through which internal strengths and external collaborations are translated into coherent, sustainable operational models.

The framework therefore operates as a composite lens through which the complexity of RI sustainability can be more effectively understood.

Structure of the Framework

The conceptual framework comprises three interconnected layers (Midgley & Arya, 2022:8-12):

Layer 1: Internal Capability Base (RBV)

This layer captures the resource profile of the RI specialised research equipment, human capital, accreditation, regulatory capabilities, institutional reputation, and knowledge assets (Ramoutar-Prieschl & Hachigonta, 2020). These resources are the starting point for determining where the RI holds advantage and where capability gaps may hinder sustainability.

Layer 2: Collaborative Knowledge Ecosystem (OI)

Surrounding the internal capability base is the RI's network of external partners, which includes universities, government agencies, industry, donors, and global research consortia (Pulford *et al.*, 2023). Through inbound and outbound knowledge flows, these actors provide access to complementary expertise, advanced technology, data-sharing arrangements, and co-funded research opportunities (Leitão *et al.*, 2020). Effective participation in this ecosystem strengthens the RI's absorptive capacity and mitigates structural constraints common in developing economies.

Layer 3: Business Model Innovation Processes (BMI)

The third layer comprises the strategic and operational mechanisms that enable the RI to redesign how it creates, delivers, and captures value (Midgley & Arya, 2022; Scott & Manning, 2022:149). BMI activities include revenue diversification, restructuring of partner relationships, integration of digital research platforms, enhancement of governance processes, and alignment with sustainability commitments (Jürgens *et al.*, 2024; Omidvar *et al.*, 2025). This layer provides the dynamic capacity needed to convert internal and external inputs into sustainable outcomes (Jürgens *et al.*, 2024).

The integrated representation in Figure 6 captures the interaction between these three layers, showing how internal resources and external networks interact through business model innovation to generate sustainable scientific, financial, and societal value.

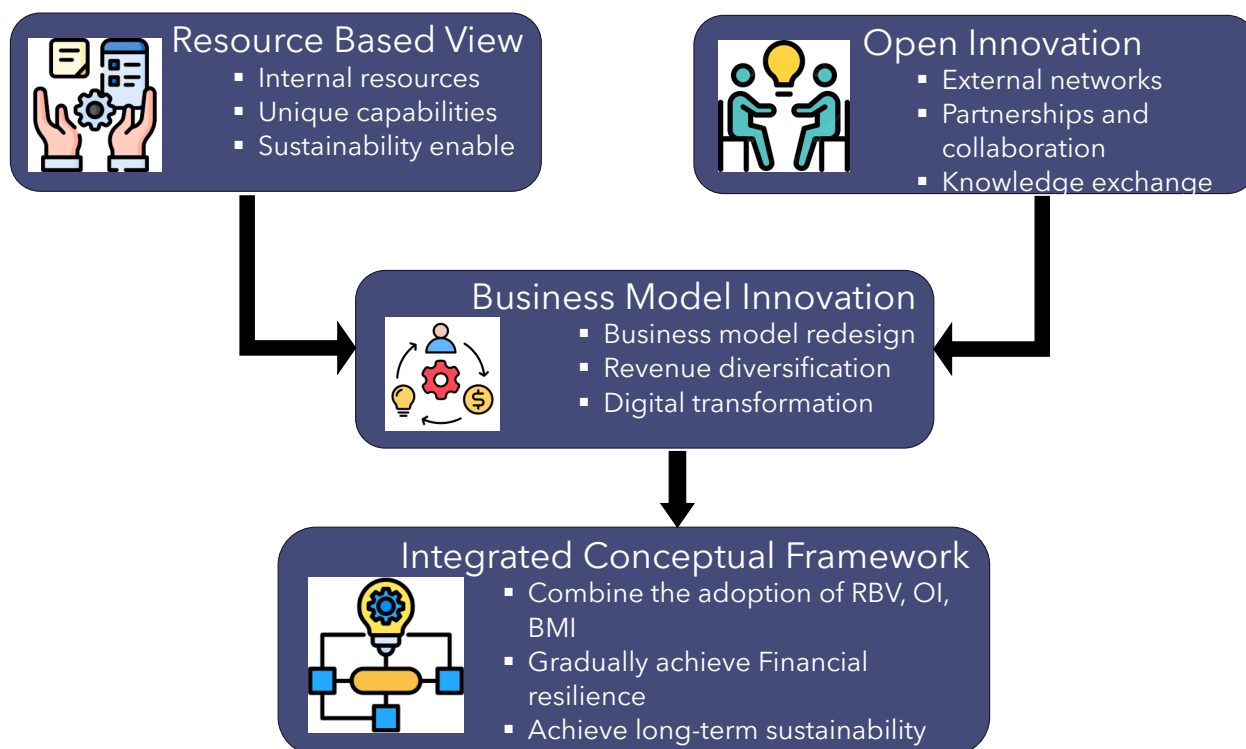


Figure 6: Integrated conceptual framework illustrating the interaction between the Resource-Based View, Open Innovation, and Business Model Innovation in supporting sustainable research infrastructures.

Relevance for Research Infrastructures in Developing Economies

The framework has particular relevance for RIs operating in resource-constrained environments. Developing economies face challenges that include funding volatility, limited access to advanced technologies, skills shortages, rigid regulatory systems, and uneven levels of institutional maturity (Falcone, 2023; Wangg *et al.*, 2023). These conditions make it difficult for RIs to rely solely on internal capabilities or external collaborations for sustainability.

By integrating RBV, OI, and BMI, the framework offers a more realistic representation of how RIs can navigate these challenges. Internal resources must be continuously strengthened, external collaborations strategically leveraged, and business model architectures deliberately redesigned to improve resilience (Malisić *et al.*, 2025). This integrated logic acknowledges that RIs cannot rely on one-dimensional approaches to sustainability in environments marked by uncertainty and systemic constraints.

Illustrative Application to the PCDDP

Although this article is conceptual rather than empirical, the value of the framework can be illustrated using the Preclinical Drug Development Platform (PCDDP) as an example (Figure 7).

The PCDDP possesses distinctive resources, including GLP-accredited facilities, specialised human capital, and established scientific credibility. It also operates within an extended network of universities, pharmaceutical actors, and public-sector agencies. However, like many RIs, the PCDDP faces funding pressures and structural constraints.

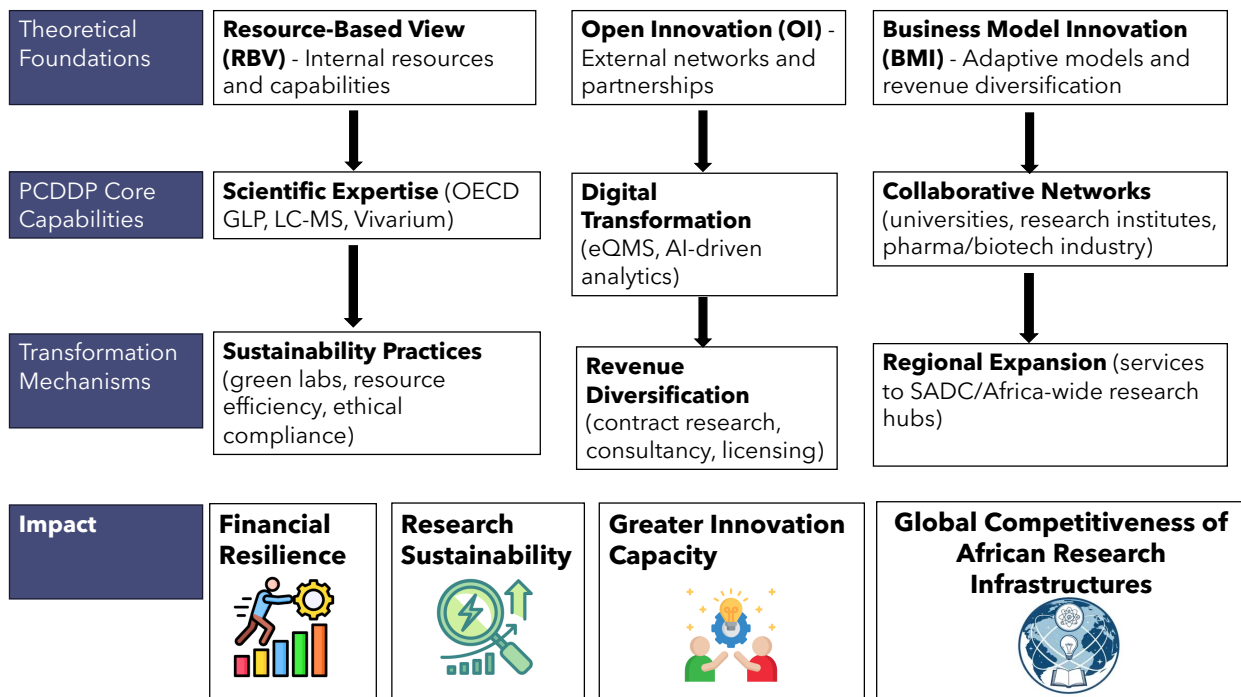


Figure 7: Application of the integrated RBV–OI–BMI framework to the Preclinical Drug Development Platform (PCDDP), demonstrating how resource capabilities, external partnerships, and business model innovation pathways interact to enhance long-term sustainability and innovation performance.

Applying the integrated framework shows that:

- RBV explains the platform’s unique scientific and institutional strengths.
- OI accounts for how the PCDDP can leverage partnerships to expand capacity and maintain relevance.
- BMI clarifies how the platform can redesign its business model through digital transformation, new service offerings, and diversified revenue channels to support long-term sustainability.

This application demonstrates the framework’s relevance for both strategic planning and institutional development within RIs.

Theoretical Contributions

This paper makes four distinct theoretical contributions to the literature on business model innovation, open innovation, and research infrastructure sustainability. Each contribution emerges from the integration of RBV, OI, and BMI and reflects the conceptual advancement needed to address the unique characteristics of research infrastructures, particularly in developing economies.

Contribution to Business Model Innovation Literature

The paper extends Business Model Innovation (BMI) theory into the domain of research infrastructures, a context that has received limited attention in mainstream business model literature. Existing BMI literature focuses predominantly on commercial firms, entrepreneurial ventures, platform ecosystems, and digital enterprises (Huang & Ichikohji, 2023; Lichy *et al.*, 2024:381; Li, 2025). By applying BMI to scientific research facilities, organisations whose missions combine public-good objectives, regulatory obligations, and specialised scientific outputs, the article demonstrates that BMI can be meaningfully adapted to hybrid, mission-driven environments.

This contributes to the broader literature by showing that business model reconfiguration is not only relevant for market-facing firms but is also essential for non-profit, public-sector, and scientific organisations seeking long-term sustainability.

Contribution to Open Innovation Scholarship

The paper advances OI theory by conceptualising research infrastructures as innovation intermediaries embedded within dynamic knowledge ecosystems. While OI literature and studies acknowledge the importance of collaboration in technology-intensive industries (Leitão *et al.*, 2020; Pulford *et al.*, 2023; Helm *et al.*, 2025), it has rarely examined the structural and regulatory constraints faced by scientific infrastructures in developing economies.

By integrating OI into an RI-specific framework, the article highlights how inbound and outbound knowledge flows are shaped by accreditation requirements, ethical oversight, resource scarcity, and public accountability. This reconceptualisation positions RIs as both contributors to and beneficiaries of distributed innovation systems, providing a more nuanced understanding of how OI operates in non-commercial, resource-constrained settings.

Contribution to Resource-Based View

The paper extends the RBV by applying VRIN/VRIO logic to the unique resource profiles of research infrastructures. It demonstrates that RIs hold distinctive tangible and intangible resources such as accredited facilities, specialised scientific expertise, institutional reputation, regulatory trust, and longitudinal data, that can offer strategic advantage but require continuous renewal to remain valuable (Mailani *et al.*, 2024:1-2; Navarro-García *et al.*, 2024).

The framework highlights that RBV alone is insufficient for explaining sustainability in RIs unless complemented by theories that account for collaborative knowledge flows and strategic business model design. This contextualised application of RBV therefore contributes to the literature by showing how internal capabilities interact with external networks and organisational strategy to influence sustainability in public scientific institutions.

Contribution to African STI Systems and RI Scholarship

A final and significant contribution lies in the contextualisation of these three theoretical perspectives to the realities of research infrastructure ecosystems in developing economies, particularly in Africa. The paper synthesises global theoretical frameworks and adapts them to environments characterised by funding volatility, skills shortages, governance complexity, and fragmented innovation systems. The framework therefore provides conceptual clarity for scholars examining African science, technology, and innovation systems by offering a model that reflects the structural constraints and opportunities within these environments. This supports the emerging literature on sustainable scientific infrastructure and contributes to knowledge on how developing economies can strengthen their research capabilities and innovation performance (Jürgens *et al.*, 2024; Omri & Almoshaigh, 2025).

Practical Implications

The integrated RBV-OI-BMI framework offers several practical implications for research infrastructure managers, policymakers, and funding stakeholders, particularly within developing economy contexts where resource constraints and institutional vulnerabilities are more pronounced. These implications translate the conceptual contributions of the article into actionable insights that can strengthen the governance, sustainability, and strategic positioning of RIs.

Implications for RI Managers

RI managers face the challenge of balancing scientific excellence with financial sustainability and organisational resilience (Kolar *et al.*, 2023; OECD, 2025). The framework provides clear direction for strategic decision-making in the following areas:

Enhancing internal capabilities

Managers can use the RBV lens to identify which resources be it technical, human, regulatory, or reputational, constitute the RI's strategic strengths and where capability gaps threaten long-term viability. This supports more targeted investment in talent development, digital systems, and accreditation readiness (Mahapatra & Dash, 2022:83; Herdian, 2025).

Leveraging collaborative networks

The OI perspective highlights the importance of structured partnerships with universities, government entities, industry actors, and international networks. RI managers should formalise collaboration mechanisms, strengthen relationship governance, and ensure that the institution develops adequate absorptive capacity to benefit from external knowledge flows (Arsanti, *et al.*, 2024; Hameed *et al.*, 2025).

Redesigning business models

The BMI component of the framework offers operational guidance on diversifying revenue streams, integrating digital systems, expanding service offerings, and aligning organisational structures with sustainability commitments. Through deliberate business model redesign, managers can reduce reliance on single-source funding and improve institutional flexibility (Grego *et al.*, 2024; Machado *et al.*, 2024; Scheepers *et al.*, 2024:1106).

Implications for Policymakers

National and provincial policymakers play a central role in shaping the regulatory and funding environments in which RIs operate (Ramoutar-Prieschl & Hachigonta, 2020). The framework offers several policy-relevant insights:

Designing supportive funding models

The integration of RBV and BMI emphasises the need for multi-year, lifecycle-based funding mechanisms that support both operational stability and strategic renewal (Wang *et al.*, 2025; Cruz-Sánchez *et al.*, 2026). Policymakers can use the framework to develop funding instruments that reward collaboration, strengthen capability development, and reduce duplication across RIs.

Improving regulatory alignment

Accreditation, biosafety requirements, and public accountability shape how RIs operate (Mahapatra & Dash, 2022:83; Herdian, 2025). Policymakers can strengthen the sustainability of RIs by ensuring that regulatory frameworks are predictable, streamlined, and aligned with global standards, thereby enabling RIs to participate more readily in international research networks.

Strengthening national innovation systems.

By recognising RIs as critical nodes within broader innovation ecosystems, not merely cost centres, the framework supports policies that incentivise cross-sector collaboration, joint research programmes, and infrastructure-sharing arrangements across scientific institutions.

Implications for Funders and Donors

Funding agencies, philanthropic organisations, and international partners are instrumental in enabling RIs to expand capacity, upgrade infrastructure, and pursue strategic collaborations (Taylor *et al.*, 2023; Jürgens *et al.*, 2024). The proposed framework supports funders in several ways:

Prioritising capability-building investments

The RBV lens indicates that investments in human capital, digital platforms, and accreditation systems yield long-term strategic value (Mailani *et al.*, 2024:1). Funders can prioritise grants that support these foundational capabilities.

Encouraging collaborative and cross-institutional projects

OI highlights the importance of knowledge-sharing networks (Asanti *et al.*, 2024). Funders may therefore design programmes that incentivise multi-institutional partnerships, co-funded research, and international collaborations.

Supporting business model transformation

BMI emphasises the need for RIs to develop diversified, resilient business models (Menter *et al.*, 2024:926). Funders can support this transformation through grants focused on digitalisation, service innovation, and hybrid revenue models that align with sustainability objectives.

The practical implications derived from the integrated framework offer actionable guidance for strengthening research infrastructures in developing economies. They bridge theory and practice by demonstrating how strategic resource management, structured collaboration, and business model redesign can help RIs achieve long-term sustainability and enhance their contribution to national and continental innovation systems.

Conclusion

This paper examined the sustainability of research infrastructures through a conceptual integration of the RBV, OI, and BMI. While each theoretical lens offers distinct explanatory value, none alone provides a sufficiently comprehensive foundation for understanding the multifaceted sustainability challenges faced by research infrastructures, particularly in developing economies marked by funding volatility, capability constraints, and complex governance environments.

By synthesising the three perspectives, the paper developed a conceptual framework that captures the dynamic interaction between internal capabilities, external knowledge flows, and strategic business model redesign. RBV clarifies the importance of distinctive resources and scientific capabilities; OI demonstrates how collaborative networks expand and renew these capabilities; and BMI provides the operational mechanisms through which both internal and external strengths can be aligned with sustainability requirements. Together, these lenses offer a multidimensional view of how RIs can enhance their organisational resilience, financial stability, and innovation performance.

The framework advances theoretical understanding by extending business model innovation into the domain of publicly oriented scientific infrastructures, positioning RIs as active participants in distributed innovation systems, and contextualising global theories to the realities of African science, technology, and innovation ecosystems. The conceptualisation also offers practical guidance for RI managers, policymakers, and funders seeking to strengthen research capability, deepen collaboration, and design sustainable operational models.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

This chapter outlines the research design and methodological procedures employed to investigate how innovation and sustainability are conceptualised and operationalised within South African research infrastructures, with specific reference to the Preclinical Drug Development Platform (PCDDP). The methodological choices were guided by the study's aim to examine the interaction between institutional capabilities, collaborative practices, and business model innovations that influence long-term sustainability in research infrastructures.

Given the complexity of organisational dynamics in research infrastructures and the nature of the available evidence, the study adopts a qualitative research design grounded in a critical realist paradigm and an abductive analytical orientation (Stutchbury, 2021:113; Keong *et al.*, 2023). A single case study strategy is used to enable an in-depth examination of the PCDDP within its institutional and policy context. Data were generated primarily through systematic document analysis supported by thematic coding in ATLAS.ti and strengthened through comparative benchmarking against national and international research infrastructure frameworks.

The remainder of the chapter presents the philosophical foundations of the study, the research approach and design, sampling procedures, data sources, document analysis protocol, thematic analysis, benchmarking logic, and the measures used to ensure trustworthiness. Ethical considerations and methodological limitations are also discussed.

3.2 Research Paradigm: Critical Realism

The study is positioned within a critical realist paradigm, which provides a suitable philosophical foundation for examining the complex organisational and structural factors that shape sustainability and innovation in research infrastructures (Stutchbury, 2021:113; Keong *et al.*, 2023). Critical realism assumes a realist ontology, in which underlying structures, mechanisms, and institutional arrangements exist independently of human perception; however, it also acknowledges a relativist epistemology, meaning that knowledge of these mechanisms is partial, fallible, and socially mediated (Keong *et al.*, 2023; Cobs-Muñoz & Westerholt, 2025:41-42). This dual stance enables researchers to recognise that observed organisational practices are influenced by deeper causal forces that may not be directly visible in documentary records but can be inferred through systematic analysis.

Critical realism is particularly appropriate for this study for three reasons. First, research infrastructures operate within layered environments comprising scientific, regulatory, financial, and policy structures (Wood *et al.*, 2013). Understanding sustainability therefore requires recognition of both observable practices and the underlying institutional mechanisms governing them. Secondly, the paradigm supports the identification of causal tendencies, enabling the researcher to move beyond describing what is contained within documents to explaining why specific patterns of innovation, capability development, or sustainability challenges arise (Pervin & Mokhtar, 2022). Finally, critical realism accommodates the interpretive processes inherent in qualitative research by acknowledging that documents reflect constructed representations shaped by institutional actors, while still enabling analytical engagement with deeper organisational realities (Ongaro & Yang, 2024:477-479).

By adopting a critical realist stance, the study can explore how internal capabilities, collaborative relationships, and business model configurations interact within the broader structural context of South African research infrastructures. This paradigm underpins the abductive reasoning and thematic analysis used in later stages of the research, ensuring coherence between philosophical assumptions and methodological procedures.

3.3 Research Approach: Abductive Reasoning

An abductive research approach was adopted to support the study's aim of developing an explanatory understanding of innovation and sustainability within research infrastructures. Abduction is particularly suited to organisational studies characterised by complex, multi-layered phenomena, as it enables the researcher to move iteratively between empirical observations and established theoretical constructs (Kistruck & Shantz, 2022). Rather than merely generating themes inductively from the data or applying theory deductively, abduction facilitates the development of plausible interpretive explanations by repeatedly refining insights in light of both evidence and theory.

This study employs abduction in two principal ways. First, documentary evidence from the PCDDP and relevant policy frameworks was examined to identify recurring patterns related to capability development, collaborative practices, governance, and sustainability challenges. These patterns were then considered in relation to the conceptual lenses outlined in Chapter 2—namely the Resource-Based View, Open Innovation, and Business Model Innovation—to explore how the data aligned with or diverged from theoretical expectations. Secondly, as coding progressed, emerging themes informed further examination of documents, allowing theoretical propositions to be refined as new insights surfaced. This iterative movement between data and theory is consistent with the critical realist goal of identifying underlying causal mechanisms rather than describing surface-level events.

Abduction therefore provides a coherent methodological bridge between the study's philosophical foundations and its analytical procedures. It supports the exploration of deeper organisational tendencies within the PCDDP and within South African research infrastructures more broadly, while maintaining the flexibility required to interpret meaning from documentary materials that vary in form, purpose, and level of detail. This approach ensures that the study's findings are grounded in the empirical evidence while remaining theoretically informed and contextually meaningful.

3.4 Research Design: Single Case Study Strategy

The study employs a qualitative single case study design, which is well suited to investigating complex organisational phenomena within their real-life context. Case study research enables the detailed examination of contemporary issues where the boundaries between the phenomenon and the context are not clearly defined (Yin, 2018). This makes it appropriate for analysing research infrastructures, which operate within intertwined scientific, regulatory, financial, and institutional environments.

The Preclinical Drug Development Platform (PCDDP) was selected as the focal case for three reasons. First, it represents a strategically significant research infrastructure within the South African national system of innovation, offering GLP-accredited preclinical testing capabilities that are rare in the region. This positions the PCDDP as an exemplar for understanding capability development, sustainability challenges, and business model innovation in publicly supported scientific infrastructures. Secondly, the PCDDP is directly relevant to the study's research questions, as its operational model reflects the interplay between internal resources, external collaborations, and evolving sustainability pressures highlighted in Chapter 2. Thirdly, the PCDDP provides access to a rich corpus of institutional documentation that enables a thorough qualitative examination of organisational dynamics over time.

The unit of analysis for this study is the PCDDP as an organisational entity, including its strategic positioning, operational practices, collaborative arrangements, and institutional environment. Although the study does not include interviews or direct observation, the depth and diversity of the documentary evidence enable a comprehensive reconstruction of the PCDDP's evolution, strategic responses, and sustainability trajectory. The single-case design therefore facilitates analytic generalisation to theory, rather than statistical generalisation, allowing insights to be interpreted in relation to the broader conceptual framework developed earlier in the dissertation.

This design aligns with the study's abductive orientation: it provides a structured yet flexible platform for iteratively engaging with empirical evidence and theoretical constructs, enabling the development of plausible, well-substantiated explanations for the observed sustainability dynamics within research infrastructures.

3.5 Justification for Selecting the PCDDP as the Case Study

The Preclinical Drug Development Platform (PCDDP) was selected as the single case for this study because it represents a strategically significant and analytically rich example of a research infrastructure operating within the South African national system of innovation. As one of the few Good Laboratory Practice (GLP)-accredited preclinical testing facilities in the country, the PCDDP fulfils a critical role in enabling pharmaceutical innovation, supporting translational research, and advancing national health research priorities. Its distinctive position within the research ecosystem makes it an appropriate and relevant unit of analysis for examining sustainability and business model innovation in research infrastructures.

The PCDDP exhibits characteristics that align directly with the study's research objectives. It operates in a resource-constrained environment, depends on a hybrid funding model, and is guided by regulatory and accreditation imperatives that shape its operational and strategic decisions. These features reflect broader systemic conditions affecting South African research infrastructures, thereby allowing insights gained from the case to extend beyond the immediate institutional setting. The platform also provides a rich body of documentation suitable for qualitative analysis, including strategic plans, operational records, business model evaluations, financial documents, and policy-linked institutional reports. The availability and diversity of these materials enable a robust examination of organisational evolution, internal capabilities, collaborative arrangements, and sustainability challenges over time. This aligns well with the abductive, document-based methodological approach adopted in the study.

Importantly, the PCDDP is embedded within national policy instruments such as the South African Research Infrastructure Roadmap (SARIR) and is shaped by national science and technology strategies. Its development trajectory is therefore influenced by both institutional and broader system-level mechanisms, making it a useful exemplar for evaluating how research infrastructures navigate the intersection of internal capability constraints, external knowledge networks, and sustainability imperatives.

For these reasons, the PCDDP offers an information-rich and theoretically relevant context within which to explore the central research questions. The findings derived from this case have potential to inform managerial practice, policy development, and future research on sustainability in publicly supported scientific infrastructures in South Africa and comparable developing-economy settings.

3.6 Data Collection Methods

Given the qualitative nature of this study and its emphasis on understanding organisational processes and sustainability dynamics within research infrastructures, data collection relied primarily on document analysis supported by comparative benchmarking. These methods are well-

suited to contexts where rich documentary evidence exists and where organisational phenomena must be examined over time and across multiple institutional layers (Bowen, 2009; Dalglish *et al.*, 2020).

3.6.1 Document Analysis

Document analysis constituted the central data collection method. This involved the systematic review and interpretation of institutional, strategic, operational, and policy documents relating to the PCDDP and the broader South African research infrastructure landscape. Consistent with the READ approach (Dalglish *et al.*, 2020), four procedural steps were followed:

1. Ready the materials by identifying and assembling relevant documents aligned with the research objectives.
2. Extract data by undertaking an initial coding of content relevant to innovation, sustainability, business model design, and operational performance.
3. Analyse the data through iterative thematic refinement using ATLAS.ti.
4. Distil insights by synthesising patterns across internal and external documents and linking them with the study's theoretical frameworks.

Documents analysed included strategic plans, business model evaluations, operational records, financial statements, policy frameworks, benchmarking reports, and grey literature. A complete list of all document types is provided in Table 3. This approach ensured comprehensive coverage of organisational practices and their evolution across the period under review.

3.6.2 Comparative Benchmarking

To contextualise PCDDP's practices within broader national and international standards, comparative benchmarking was incorporated as a supplementary method. This involved analysing policy documents from bodies such as the Department of Science and Innovation (DSI), the South African Research Infrastructure Roadmap (SARIR), the National Science and Technology Forum (NSTF), and international organisations such as the OECD.

Benchmarking served three purposes:

- to situate PCDDP within national research infrastructure strategy and performance expectations
- to evaluate alignment with emerging global practices in research infrastructure sustainability
- to identify gaps and strengths that informed the interpretation of thematic findings

This dual-method design provided both depth (through internal documentation) and breadth (through external comparison), enabling robust triangulation of findings.

3.6.3 Search Strategy and Documentation Procedures

A structured search strategy was applied to ensure systematic and transparent document retrieval. Figure 8 illustrates the full search workflow, showing how organisational documents and policy frameworks were identified, screened, and included

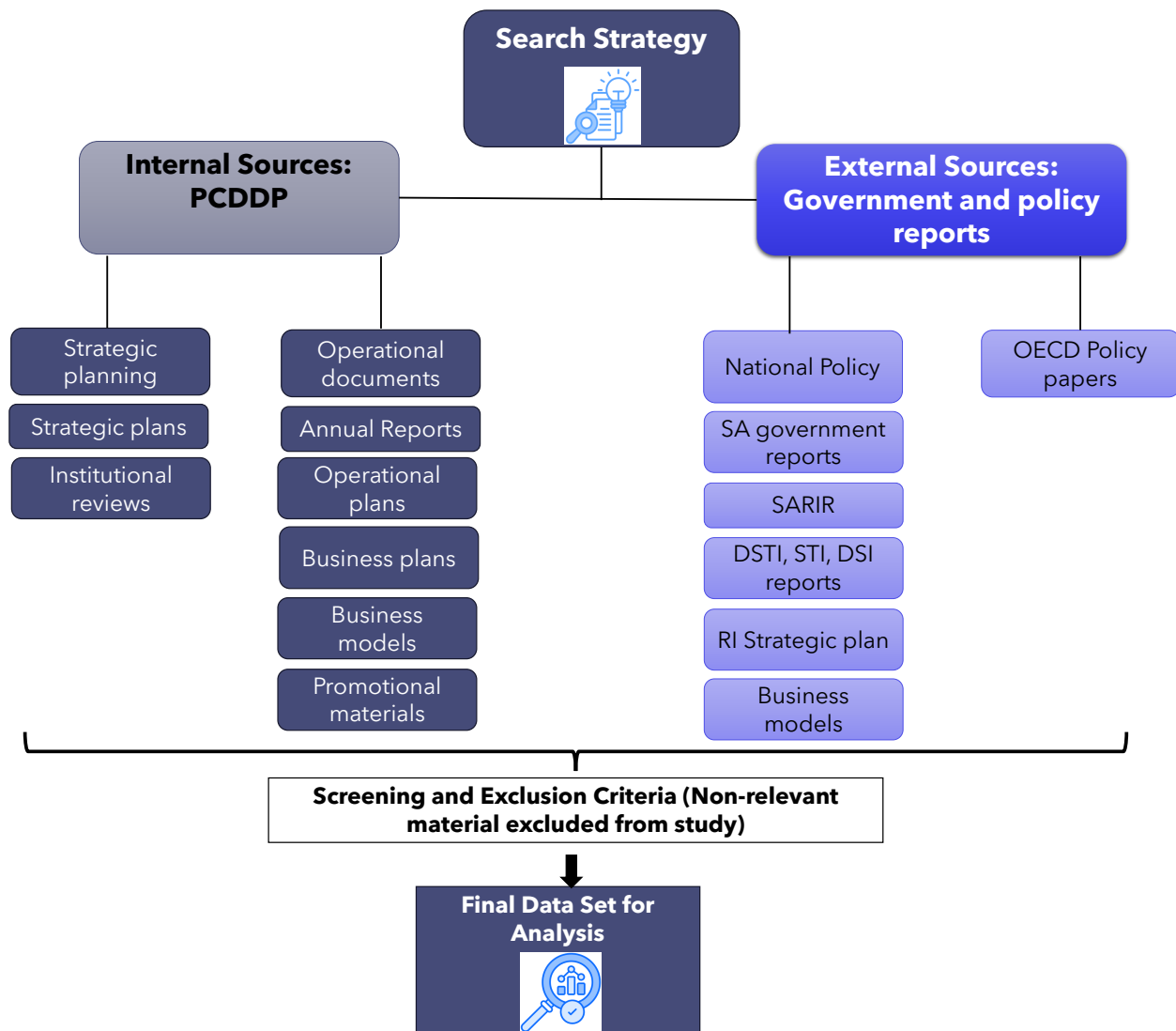


Figure 8: Search strategy deployed in the study

Searches used predefined keywords (Table 2) and were conducted across institutional repositories, policy databases, and academic indexing services, including NWU repositories, DST/DSI resources, SARIR documentation, OECD STIP Compass, Sabinet, Scopus, Web of Science, and Google Scholar.

Table 2: Thesis theme and keywords used in database search

Theme	Primary Keywords / Search Terms	Filters / Parameters Applied
Innovation and Sustainability in Research Infrastructures (RIs)	“research infrastructure”, “innovation infrastructure”, “scientific infrastructure sustainability”, “digitalisation in RIs”, “RI sustainability challenges”, “public–private collaboration in science”, “research facility management”	Timeframe: 2010–2025; Document type: policy documents, strategic plans, academic literature
Business Models and Business Model Innovation in RIs	“business model innovation”, “RI business models”, “sustainability-oriented innovation”, “commercialisation in research organisations”, “industry–academia collaboration”, “contract research models”, “innovation ecosystems”	Sector filter: science, technology, and innovation; Document type: academic/grey literature
South African Policy and Funding Frameworks	“South Africa research infrastructure policy”, “DSI strategy”, “SARIR roadmap”, “national innovation policy”, “STI Decadal Plan”, “NIHSS”, “NRF strategy”, “public research funding South Africa”	Geographic filter: South Africa; Source filter: DSI, SARIR, NSTF, NRF, CSIR
Global Benchmarking of Research Infrastructures	“OECD research infrastructures”, “international RI benchmarking”, “global RI sustainability models”, “European research infrastructures”, “ESFRI”, “NSF research infrastructure models”, “best practice in research infrastructure management”	Filters: OECD, EU, high-performing innovation systems (Germany, Sweden, Finland, Netherlands)

All searches were recorded in a document log capturing search terms, databases used, retrieval dates, and number of results. This audit trail supports replicability and methodological transparency (Gertler & MacDonald, 2025).

3.7 Document Analysis

Document analysis served as the primary data collection method for this study. It enabled a systematic and context-sensitive examination of institutional, operational, strategic, and policy documents relating to the PCDDP and to the broader South African research infrastructure environment. As research infrastructures generate substantive written records that capture organisational priorities, governance practices, performance trajectories, and interactions with national policy frameworks, document analysis provides an appropriate and rigorous means of accessing these organisational dynamics (Bowen, 2009; Dalglish *et al.*, 2020).

Consistent with the READ approach proposed by Dalglish *et al.* (2020), the analysis followed four interlinked procedural steps:

1. **Ready** – All relevant documents were identified, assembled, and screened according to the inclusion criteria outlined in Section 3.3. This stage focused on establishing document relevance, credibility, and completeness across the timeframe under review.
2. **Extract** – Preliminary coding was conducted to identify text segments relating to innovation practices, sustainability challenges, business model evolution, collaborative arrangements, capability development, and governance processes. ATLAS.ti was used to organise and manage these extracts systematically.
3. **Analyse** – Codes were refined and merged into higher-order themes through iterative comparison and cross-document synthesis. This analytic process was informed by abductive reasoning, enabling movement between the emerging themes and the theoretical frameworks set out in Chapter 2.
4. **Distil** – Patterns and causal tendencies were synthesised into thematic findings that explained how the PCDDP navigates sustainability pressures, capability constraints, and innovation opportunities. These findings were subsequently interpreted against RBV, Open Innovation, and Business Model Innovation perspectives to deepen theoretical insight.

The dataset comprised strategic plans, business model evaluations, operational documents, policy frameworks, benchmarking reports, institutional performance materials, and grey literature. Table 3 presents the document categories and types included in the analysis.

Table 3: Types of Documents and Data Collected for the Study

Category	Document Type	Description / Purpose	Timeframe
A. PCDDP Institutional and Strategic Documentation	Strategic Plans	Long-term institutional positioning, organisational priorities, and sustainability goals.	2022–2025
	Strategic Workshop Outputs	Workshop presentations, planning notes, and facilitation materials reflecting organisational development and strategic reorientation.	2022–2025
	DST/NWU PCDDP Business Plan	Foundational business plan outlining mandate, funding model, and operational structure.	2011
	Business Model Evaluation Reports	Formal evaluations of the PCDDP's business model and recommendations for improvement.	2024–2025

Category	Document Type	Description / Purpose	Timeframe
	Operational Plans	Internal planning and implementation documents, including workflow, budgetary planning, and capacity allocation.	2020–2025
	Institutional Performance Reviews	Internal presentations and performance assessments highlighting achievements and operational constraints.	2022–2025
	Promotional Materials	Posters, brochures, and other communication artefacts reflecting strategic positioning and stakeholder engagement.	2020–2025
	Standard Operating Procedures (SOPs) and Compliance Records	GLP-related SOPs, pricing schedules, digital quality systems (eQMS), and compliance documentation.	2020–2025
B. National Policy and Strategic Frameworks	National Research Infrastructure Roadmaps	SARIR roadmaps and related presentation materials outlining national priorities and infrastructure classifications.	2013, 2021
	DSI/DST Strategic Plans	National science, technology, and innovation strategic directives.	2020–2025; 2025–2030
	STI Decadal Plan	National long-term planning document guiding the STI system.	2022–2032
	National Indicators Reports	National STI performance indicators and benchmarking.	2023
	Institutional Landscape Reviews	Ministerial reviews of the higher education and research ecosystem (HESTIIL Report).	2020
	Sectoral Innovation Reports	Examples include Innovation in TVET Colleges reports and related policy briefs.	2021
	NRF and CSIR Strategies	Institutional strategies from major national research actors relevant to PCDDP's environment.	2020s–2025
C. International Policy, Benchmarking, and Comparative Documentation	OECD Policy Papers	OECD research infrastructure frameworks, operation guidelines, and impact assessment methodologies.	2019–2025

Category	Document Type	Description / Purpose	Timeframe
	OECD Very Large Research Infrastructure Reports	International best practice and sustainability models.	2023
	NSTF Reports	National reflection reports on challenges in the research and innovation system.	2023–2024
D. Academic and Expert Literature	Books	Foundational literature on RI management, e.g., <i>Management of Research Infrastructures: A South African Funding Perspective</i> .	2020
	Peer-reviewed Journal Articles	Academic literature on business models, innovation, sustainability, research infrastructures, and policy systems.	2010–2025
	Working Papers and Grey Literature	Policy briefs, expert reports, and institutional commentary relevant to RIs.	2010–2025

The strength of document analysis lies in its ability to capture both the historical evolution and contemporary strategic positioning of the PCDDP. By integrating internal documents with external policy and benchmarking sources, the method provided a holistic view of how organisational practices interact with broader national systems of innovation. This multi-layered examination allowed for the identification of long-term patterns not readily accessible through interview-based or cross-sectional methods.

Document analysis therefore served as the backbone of the empirical inquiry, offering both depth and breadth while remaining aligned with the critical realist objective of uncovering underlying mechanisms shaping sustainability and innovation in research infrastructures.

3.8 Comparative Benchmarking

Comparative benchmarking was employed as a complementary analytic strategy to situate the PCDDP within the broader landscape of national and international research infrastructures. Benchmarking is widely recognised as an effective method for identifying strengths, gaps, and opportunities for organisational improvement through systematic comparison against relevant peers or established standards (Dehe *et al.*, 2022). In the context of this study, benchmarking served to enhance analytical depth by providing an external reference point for interpreting the PCDDP’s innovation practices, sustainability challenges, and business model configuration.

The benchmarking analysis drew on national policy frameworks, international guidelines, and institutional strategy documents from comparable research infrastructures. These included the South African Research Infrastructure Roadmap (SARIR), the Department of Science and Innovation (DSI) strategic documents, National Science and Technology Forum (NSTF) reflections, and internationally recognised frameworks developed by the OECD and European Strategy Forum on Research Infrastructures (ESFRI). These sources were selected because they articulate performance expectations, governance principles, sustainability criteria, and operational models that are relevant to the management of publicly funded scientific infrastructures.

The benchmarking process followed three steps:

(1) Identification of benchmark domains

Domains were selected based on relevance to the study's theoretical lens and research objectives. These domains included capability development, governance and compliance structures, digital and technological maturity, funding and revenue models, collaboration intensity, and sustainability practices.

(2) Extraction and comparison of performance indicators

Documentary sources were examined to extract principles, indicators, and recommended practices. Examples include funding diversification strategies outlined in OECD policy papers, operational standards reflected in GLP and international research facility guidelines, and collaboration norms embedded in European research infrastructure models. These were compared with the practices observed in PCDDP documents to determine alignment, gaps, or divergence.

(3) Synthesis and interpretation

The benchmarking findings were interpreted abductively, linking observed patterns to the theoretical constructs outlined in Chapter 2. This enabled a contextualised understanding of how PCDDP's strengths and constraints reflect broader structural conditions in South Africa's research system, as well as how international best practices illuminate potential pathways for organisational improvement.

The value of comparative benchmarking in this study lies in its ability to situate internal organisational evidence within a broader systems perspective. For instance, recurring patterns in national documents, such as funding instability, skills shortages, and infrastructure maintenance deficits, mirror the challenges observed in the PCDDP's internal records. Conversely, international benchmarks highlight practices that PCDDP has not yet fully incorporated, such as structured innovation ecosystems, digital research integration at scale, and multi-tiered revenue frameworks. Benchmarking thus strengthens the explanatory weight of the thematic findings by demonstrating how the PCDDP's organisational dynamics reflect both internal capabilities and wider systemic

constraints. This reinforces the critical realist objective of identifying causal tendencies operating at different institutional levels and enhances the credibility of the interpretations developed in Chapter 4.

3.9 Thematic Analysis (ATLAS.ti)

Thematic analysis was used as the principal analytic technique for interpreting the documentary dataset. This method is widely recognised for its flexibility and suitability in qualitative organisational research, particularly where the aim is to identify patterns of meaning across diverse textual materials (Braun & Clarke, 2006; Sirwan *et al.*, 2025). Within this study, thematic analysis enabled systematic engagement with complex institutional, strategic, and policy documents, supporting an interpretive understanding of how innovation, sustainability, and business model dynamics manifest within the PCDDP.

ATLAS.ti was used to manage, organise, and interrogate the dataset (Ñañez-Silva *et al.*, 2024). Computer-assisted qualitative data analysis software (CAQDAS) provides analytical structure in studies involving large volumes of unstructured text, reduces the risk of oversight, and offers transparent coding trails that strengthen the credibility of findings (Ñañez-Silva *et al.*, 2024; Sharma, 2024). The software enabled consistent application of codes across multiple document types and supported iterative theme development aligned with the abductive research approach.

The thematic analysis proceeded through three interrelated stages:

(1) Pre-analysis

Documents were imported into ATLAS.ti and reviewed to gain a preliminary sense of content, structure, and relevance. Initial memos captured early observations concerning innovation practices, institutional challenges, governance processes, capability development, and sustainability pressures. This stage established analytic familiarity and informed the development of a provisional coding framework.

(2) Material exploration

A combination of inductive and deductive coding was undertaken. Deductive codes were informed by the conceptual frameworks presented in Chapter 2 (Resource-Based View, Open Innovation, Business Model Innovation), while inductive codes emerged from recurrent patterns observed in the documents. Coding proceeded iteratively, with codes refined, merged, or extended as new relationships or consistencies were identified. ATLAS.ti's query tools were used to examine code co-occurrence patterns, which assisted in identifying underlying mechanisms connecting capability constraints, partnership dynamics, funding pressures, and operational practices.

(3) Interpretation and theme development

Coded segments were reorganised into higher-order themes that represented coherent patterns across the dataset. This interpretive stage involved abductively linking emergent themes with theoretical constructs, enabling the identification of causal tendencies that shape sustainability within research infrastructures. Core themes included drivers of innovation, structural barriers, governance and regulatory influences, funding and revenue dynamics, digital maturity, and sustainability-oriented organisational practices. These themes provide the foundation for the findings presented in Chapter 4.

Throughout the analysis, reflexive memo-writing supported critical engagement with interpretive decisions, ensuring analytical transparency. The use of ATLAS.ti allowed for systematic triangulation across document types and facilitated the integration of internal institutional evidence with broader policy and benchmarking materials. Thematic analysis therefore served as the central analytic engine of the study, transforming heterogeneous documentary evidence into structured, theoretically informed insights that illuminate how research infrastructures such as the PCDDP navigate innovation and sustainability challenges within a developing-economy context.

3.10 Benchmarking Interpretation and Synthesis

Benchmarking interpretation and synthesis formed an essential step in connecting the PCDDP's documented practices with broader institutional and international standards for research infrastructure management. While Section 3.8 described the benchmarking procedure, this section outlines how benchmarking insights were integrated into the analytical process to enhance explanatory depth and contextual robustness.

Once benchmarking indicators were extracted from national policy frameworks such as SARIR, DSI strategies), institutional strategy documents such as NRF and CSIR frameworks, and international references such as OECD and ESFRI guidelines, these were compared systematically with the coded themes emerging from the PCDDP data. This comparative approach enabled the identification of convergences, divergences, and structural misalignments across domains such as governance, capability development, funding architecture, digital maturity, and sustainability practices.

Three interpretive steps guided the synthesis:

(1) Alignment assessment

Themes generated through ATLAS.ti coding were compared with benchmark expectations to assess the degree of congruence. Areas of alignment, such as adherence to GLP standards, commitment to capacity development, and participation in collaborative networks validated the

internal consistency of PCDDP's documented practices and provided evidence that certain organisational strengths reflect recognised norms within high-performing research infrastructures.

(2) Identification of gaps and constraints

Benchmarking revealed several areas where the PCDDP's documented practices diverged from international and national expectations. Examples included limited revenue diversification relative to OECD recommendations, constrained digital integration compared with international open-science models, and recurring dependencies on short-cycle public funding. These discrepancies were not treated as shortcomings but as indicators of underlying structural constraints facing research infrastructures in developing economies. This interpretive stance is consistent with the critical realist emphasis on recognising deeper causal mechanisms beyond observable patterns.

(3) Integrative explanation

Benchmarking insights were synthesised with the thematic analysis to produce richer, contextually grounded explanations of sustainability dynamics within the PCDDP. For instance, gaps identified in capability renewal or digitalisation were interpreted not only as organisational limitations but also as consequences of broader systemic conditions such as fragmented policy coordination, limited national infrastructure investment, and broader skills shortages within the South African innovation system. Similarly, areas where PCDDP exceeded benchmark expectations, such as compliance with accreditation standards and scientific positioning helped explain its resilience despite resource constraints.

The benchmarking synthesis therefore played a dual interpretive role. First, it provided an external reference point against which the internal organisational evidence could be systematically assessed. Secondly, it enhanced the explanatory power of the study by illuminating how institutional-level practices intersect with system-level mechanisms. This integrative interpretation supports analytic generalisation to the theoretical frameworks presented in Chapter 2 and strengthens the foundation for the empirical findings presented in Chapter 4.

3.11 Ethical Considerations

Ethical considerations were integral to the design and execution of this study, particularly because the research involved the analysis of institutional documentation, some of which contained sensitive operational information. While the study did not involve human participants, interviews, or observational methods, ethical rigour remained essential to ensure responsible handling of data, protection of institutional confidentiality, and adherence to North-West University's research governance protocols.

Formal permission was obtained from the Director of the PCDDP to access internal documents, including strategic plans, financial statements, operational records, business model evaluations, and compliance documentation. This permission included clear conditions regarding the handling, storage, and reporting of information. All documents were assessed for sensitivity, and any material that could identify individuals or reveal confidential operational details was anonymised or generalised during analysis and in the presentation of findings.

Data were stored securely on a password-protected university-issued device equipped with fingerprint authentication to prevent unauthorised access. No documents were stored on cloud services, external devices, or shared drives, in accordance with NWU data protection protocols. Access to the dataset was restricted to the researcher and, where applicable, the co-coder involved in the inter-coder reliability process. The co-coder likewise complied with confidentiality and data protection procedures. In line with ethical guidance on the use of secondary data, only official institutional documents and credible grey literature were included, and their provenance was verified. Grey literature was triangulated with official sources to ensure both accuracy and contextual stability. Policy documents sourced from national and international organisations were used in accordance with public-domain usage rights, and all sources were fully referenced.

The study also adhered to principles of analytical integrity. Documentary evidence was interpreted within its institutional context, avoiding decontextualised or misleading representations of organisational practice. Where limitations in document completeness or accessibility existed, these were acknowledged transparently rather than compensated for through inference beyond the available evidence. By following these ethical measures, the study ensured responsible management of institutional information, compliance with NWU ethical requirements, and alignment with national research integrity principles. The ethical approach also supports the credibility and trustworthiness of the findings by demonstrating careful stewardship of sensitive documentation and appropriate safeguards during analysis and reporting.

3.12 Limitations

As with any qualitative inquiry, this study is subject to several methodological limitations that shape the scope and interpretation of its findings. These limitations do not undermine the study's credibility but provide necessary transparency regarding factors that may influence the depth, breadth, and generalisability of the results.

First, the study relied exclusively on documentary evidence without the inclusion of interviews, direct observation, or stakeholder consultations. Although the dataset was rich and diverse, documentary sources inevitably reflect institutional priorities, reporting conventions, and organisational framing. The absence of primary accounts limits the ability to triangulate internal documents with lived organisational experiences or tacit knowledge held by staff. This limitation was mitigated through benchmarking and triangulation; however, it cannot be fully eliminated.

Second, the study adopted a single-case design focused on the PCDDP. While single-case studies enable in-depth examination and strong contextual insight, they inherently limit the generalisability of findings across the broader population of South African research infrastructures. Analytic generalisation to theory is appropriate, but empirical generalisation to other infrastructures should be undertaken cautiously. The relevance of the case was strengthened through systematic benchmarking against national and international frameworks, but case-specific conditions may still influence interpretation.

Third, not all desirable documents were accessible. Some annual reports, internal performance reviews, and historical records were missing, incomplete, or unavailable. While the study drew on the most comprehensive set of documents accessible within institutional and ethical constraints, gaps in archival completeness may affect longitudinal analysis. Care was taken to avoid speculative inference in areas where documentation was limited.

Fourth, thematic analysis is an interpretive process, and although measures such as inter-coder reliability and reflexive memoing enhanced rigour, researcher interpretation inevitably influences coding decisions and theme formation. The abductive approach further emphasises interpretation through iterative movement between theory and data. These interpretive elements are appropriate for critical realist qualitative research but represent a methodological limitation to be acknowledged.

Finally, the benchmarking analysis depended on publicly available policy frameworks and strategic documents from national and international bodies. While these sources are authoritative, they may not fully reflect the operational realities or informal practices of comparator institutions. As such, benchmarking interpretations rely on the documented representations of external infrastructures, which may differ from their lived organisational practices. Despite these limitations, the study employs rigorous methodological safeguards triangulation, systematic coding, documentary verification, inter-coder reliability, and critical realist interpretive logic, to ensure that findings remain credible, trustworthy, and analytically robust.

3.13 Chapter Summary

This chapter has outlined the methodological foundation underpinning the study. The research design was shaped by a critical realist paradigm, an abductive analytical orientation, and a qualitative single-case strategy focused on the PCDDP. These choices reflect the complexity of research infrastructures and the study's intent to uncover the underlying mechanisms influencing innovation and sustainability in a developing-economy context.

Document analysis formed the core data collection method, supported by a structured search strategy, comprehensive document inclusion criteria, and a transparent logging process to ensure methodological rigour. The use of ATLAS.ti enabled systematic thematic analysis through iterative coding, pattern identification, and abductive interpretation. Benchmarking against national and international policy frameworks provided an external reference point, strengthening both contextual understanding and analytical depth. Together, these procedures contributed to a robust and coherent methodological framework capable of addressing the study's research questions.

Trustworthiness was reinforced through triangulation, inter-coder reliability procedures, careful document verification, and adherence to strict ethical protocols governing data access, storage, and reporting. While the study is subject to limitations related to the use of documentary data, the single-case design, and the interpretive nature of qualitative analysis, these constraints were acknowledged and mitigated appropriately. Overall, the methodological approach provided a rigorous and context-sensitive platform for examining how internal capabilities, collaborative arrangements, and business model dynamics shape sustainability within a South African research infrastructure. Chapter 4 builds on this foundation by presenting the empirical findings derived from the thematic and benchmarking analyses, offering detailed insight into the innovation and sustainability practices of the PCDDP.

CHAPTER 4: RESULTS AND FINDINGS

4.1 Introduction

This case study applies a qualitative research design grounded in the methodological principles set out in Chapter 3. As the study investigates how innovation and sustainability are operationalised within a South African research infrastructure, it adopts a document-based analytical strategy that enables a systematic examination of organisational practices, strategic intent, and institutional evolution over time. The approach is rooted in critical realism and abductive reasoning, allowing the analysis to move iteratively between empirical evidence and the theoretical constructs presented in Chapter 2.

Given that the PCDDP maintains a substantial documentary record spanning strategic plans, business model evaluations, operational materials, and policy-linked institutional reports, document analysis was selected as the primary mode of inquiry. This method is well suited to research environments in which historical and strategic documents constitute the main source of organisational evidence, and where direct observation or interviews fall outside the study scope. It supports the identification of patterns, mechanisms, and contextual conditions that influence sustainability and innovation, while enabling the researcher to reconstruct organisational trajectories and strategic responses across the period under review.

The analysis followed the procedures outlined in Chapter 3, including systematic collection, coding, and thematic synthesis using ATLAS.ti. Documents were examined for content relating to capability development, collaborative practices, governance arrangements, digital transformation, financial sustainability, and alignment with national research infrastructure policy. The abductive research logic guided the interpretation of these materials, enabling the refinement of theoretical insights as empirical patterns emerged (Vila-Henninger *et al.*, 2022).

The PCDDP serves as an appropriate and analytically rich case, given its positioning within the national system of innovation and the availability of detailed institutional documentation. The case study design allows the findings to contribute to analytic generalisation rather than statistical inference, aligning with the study's aim of developing evidence-based insights into business model innovation and sustainability within research infrastructures. This methodological orientation ensures that the empirical analysis remains theoretically grounded, contextually sensitive, and aligned with the study's overarching aim: to examine how organisational resources, collaborative networks, and business model dynamics shape the sustainability trajectory of a South African research infrastructure.

4.2 Data Sources and Collection

The empirical analysis presented in this chapter draws exclusively on the documentary corpus identified through the sampling procedures detailed in Chapter 3. Because the study relies on qualitative document analysis supported by ATLAS.ti, the selection, organisation, and systematic extraction of evidence from the available materials constituted the foundation of the analytical process. The documents span the period 2011–2025, allowing for longitudinal interpretation of the PCDDP's strategic evolution, operational adaptations, business-model changes, digital-transformation processes, and sustainability trajectory.

4.2.1 Institutional and Strategic Documentation (PCDDP)

Internal documentation from the PCDDP formed the primary data source. These materials include the Perspectives on PCDDP strategic document (2022), SANAS GLP inspection presentation reports (2021–2025), performance-review portfolios (2021–2022), financial business-model evaluation reports (2024; 2025), the DST/NWU PCDDP Business Plan (2011), operational planning documents (2020–2025), pricing schedules, workflow descriptions, and GLP-related SOPs, including the transitional quality-management protocol (SOP QA DOC11 – Interim Management of SOPs During Transition to Electronic QMS). These documents provided detailed evidence of the platform's operational capabilities, accreditation processes, infrastructural upgrades, scientific positioning, and internal sustainability considerations.

4.2.2 National Policy and Planning Documents

A second data category consisted of national government policy documents that frame South Africa's research-infrastructure environment. These include the South African Research Infrastructure Roadmap (SARIR 2013; SARIR 2021 presentations), the Department of Science and Innovation's Strategic Plan 2020–2025 and Revised Strategic Plan 2025–2030, the STI Decadal Plan 2022–2032, the Science, Technology and Innovation Indicators Report 2023, and the Higher Education, Science, Technology and Innovation Institutional Landscape Review Report (2020). These documents were essential for assessing PCDDP's alignment with national priorities and understanding the systemic conditions influencing sustainability.

4.2.3 International Benchmarking and Comparative Sources

International documents were analysed to contextualise the PCDDP within global research-infrastructure practices. These include OECD policy papers (Reference Framework for Assessing Impact 2019; Optimising the Operation and Use of National Research Infrastructures 2020; Very Large Research Infrastructures 2023) and NSTF materials (2023–2024). These sources provided comparative reference points regarding governance, impact assessment, lifecycle costing, user-access models, and digital maturity.

4.2.4 Academic and Expert Literature Provided

Academic sources supplied as part of the dataset, most notably Ramoutar-Prieschl and Hachigonta's *Management of Research Infrastructures: A South African Funding Perspective* (2020), supported theoretical grounding. These texts were used solely to interpret findings and were not treated as primary data.

4.2.5 Analytical Preparation and Workflow

All documents meeting the inclusion criteria were imported into ATLAS.ti and analysed using the six-phase thematic analysis framework adapted from Braun and Clarke (2006), as operationalised in Naeem *et al.* (2023). Table 4 summarises the full analytical procedure and shows how each phase was applied specifically to the PCDDP dataset.

4.2.6 Data-Management and Audit Trail

All searches, document imports, coding iterations, and thematic refinements were recorded in a document log. The log captured the date of retrieval, document source, relevance notes, and coding status. This ensured methodological transparency and replicability, consistent with the procedures outlined in Chapter 3. No external documents beyond those explicitly provided were used.

4.3 Narrative Interpretation: Overview of Findings

This section provides an integrated narrative interpretation of the thematic patterns emerging from the ATLAS.ti documentary analysis. The findings are drawn exclusively from the dataset described in Section 4.2, comprising 41 documents, 65 primary codes, and approximately 16 800 code variants. These codes were refined and structured through the phased thematic analysis process presented in Table 4, which guided the development of five overarching themes aligned with the study's research questions.

Table 4: Thematic Analysis Process Overview (Adapted from Braun & Clarke, 2006; Naeem *et al.*, 2023).

Phase	Description of Action	Application to the Current Study (PCDDP)
Phase 1: Pre-analysis	Reading the documents to gain an in-depth understanding; creating the ATLAS.ti project	All documents were read to gain familiarity with the content. All 41 documents were uploaded into ATLAS.ti and examined for patterns relevant to the research questions.
Phase 2: Coding	Generating initial codes systematically across the dataset	A total of 65 codes and approximately 16 800 code variants were generated in response to the five research questions.
Phase 3: Searching for Themes	Collating codes into potential themes	Codes were grouped into six broader thematic clusters aligned with the research questions.
Phase 4: Reviewing Themes	Refining and consolidating themes to ensure internal coherence and external distinction	Thematic clusters were reviewed against coded extracts and refined to ensure alignment with the study objectives.
Phase 5: Defining and Naming Themes	Specifying each theme and identifying sub-themes	Final themes comprised innovation drivers, sustainability barriers, digital capabilities, international best practices, and strategic recommendations.
Phase 6: Writing Up	Integrating findings into the narrative with supporting figures and quotations	Themes were presented with supporting extracts and visualised through frequency distributions (Figure 9).

The distribution of coded material across themes is reflected in Figure 9, which demonstrates that innovation drivers and strategic recommendations constituted the two largest clusters of coded evidence, followed by barriers to sustainability, digital capabilities, and international best practices.

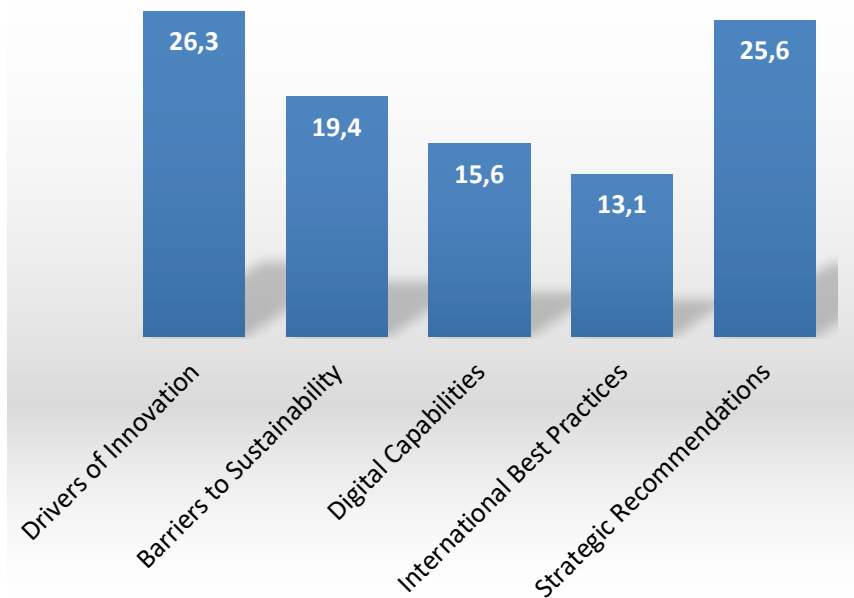


Figure 9: Percentages of code variation calculated as a percentage under each main theme.

The sunburst diagram shows a visual overview of how the thematic codes were organised across the five core analytical areas guiding this study (Figure 10). At the centre of the diagram are the five high-level themes that serve as the organising framework for the thematic codes, comprising key drivers of innovation and sustainability, barriers to sustainability, digital capabilities and efficiency, international best practices, and strategic recommendations.

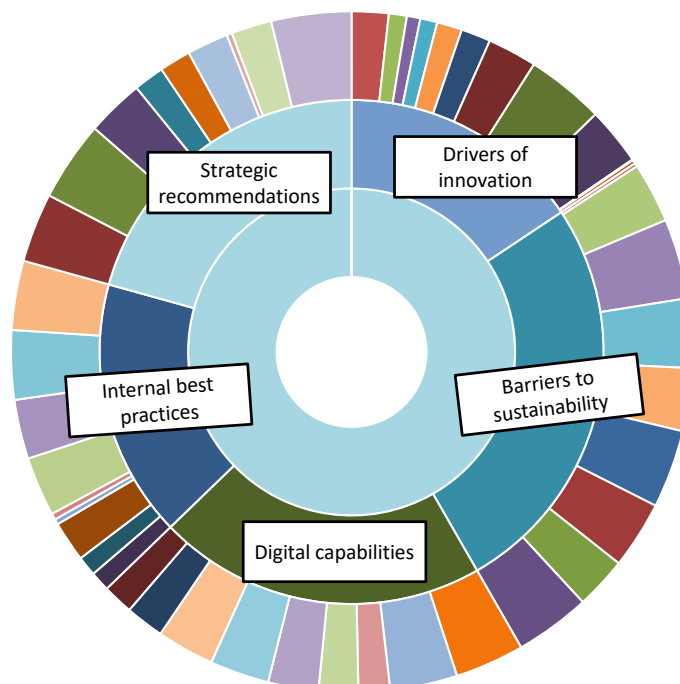


Figure 10: Sunburst diagram showing the overview of how the thematic codes were organised across the five core analytical areas guiding this study

More importantly, each outer segment shows the main code obtained from the analysis, whilst the size and distribution of these segments highlight how the data clustered around the areas.

The sunburst diagram strengthens the study's overall argument as it illustrates how the elements of innovation, sustainability, digital capability, and strategic positioning are deeply interconnected within the PCDDP context. The diagram shows how they cluster around the core themes that emerged in both the literature in chapter 2 and the empirical analysis in this chapter, thus providing a comprehensible visual summary of the complex environment in which research infrastructures operate and stressing the need for coordinated business-model innovation to achieve long-term sustainability. This visual integration reinforces the argument that sustainable research infrastructures require a systems-oriented approach, one that simultaneously addresses internal capabilities, external partnerships, operational constraints, and forward-looking strategies (Wood *et al.*, 2013; Kusmendar *et al.*, 2025).

4.4 Themes

This section outlines the five overarching themes that emerged from the thematic analysis and provides a concise overview of how each theme contributes to the study's analytical structure. The themes were derived from the 65 primary codes and approximately 16 800 code variants generated during the ATLAS.ti analysis and represent the dominant conceptual areas that appeared repeatedly across institutional, strategic, operational, policy and benchmarking documents.

The distribution of coded material presented in Figure 9 and the structural arrangement of codes illustrated in Figure 10 (both introduced in Section 4.3) confirm that the themes reflect clearly differentiated yet interrelated domains, each aligned with one of the research questions guiding the study.

The five themes are:

1. Key drivers of innovation and sustainability
2. Barriers to adopting sustainable strategies
3. The role of digital capabilities in operational and financial sustainability
4. International best practices relevant to research infrastructures
5. Strategic recommendations for integrating innovation and sustainability

These themes form the analytical pathway for the detailed findings presented in Sections 4.5 to 4.10.

Theme 1: Key Drivers of Innovation and Sustainability

This theme captures internal and external forces that enable the PCDDP to pursue innovation and strengthen sustainability. Evidence across strategy documents, GLP inspection records, performance reviews and national policy frameworks highlight scientific and technical capability, regulatory accreditation, alignment with national STI priorities, and multi-institutional collaboration as core drivers. These drivers collectively establish the PCDDP as an important national asset capable of contributing to pharmaceutical innovation, research excellence and socio-economic development.

Theme 2: Barriers to Adopting Sustainable Strategies

The second theme concerns structural, financial, operational and workforce-related constraints that hinder the adoption of sustainable business practices. These include ageing infrastructure, inconsistent digital systems, limited funding diversification, equipment-maintenance burdens, regulatory misalignment and workforce shortages. These barriers limit scalability and impede long-term planning, directly moderating the strength of the innovation drivers described above.

Theme 3: Role of Digital Capabilities in Financial Sustainability and Efficiency

Digital maturity emerged as a central determinant of sustainability. Codes linked to digital management, workflow systems, data integrity, equipment oversight and financial strategy indicate that digital capabilities enable operational reliability, cost optimisation, regulatory readiness and strategic decision-making. However, gaps remain in system integration, staff readiness and digital lifecycle planning, suggesting that digital transformation is both a driver and an ongoing challenge.

Theme 4: International Best Practices Relevant to Research Infrastructures

The fourth theme draws on global models (as reflected in the OECD, NSTF and benchmarking documents) that offer concrete lessons for improving research infrastructure sustainability. These include distributed governance structures, lifecycle costing, transparent access frameworks, maturity-model approaches to digital development, and FAIR compliance. Such practices highlight scalable pathways for the PCDDP to strengthen its operations and align with internationally recognised standards.

Theme 5: Strategic Recommendations for Integrating Innovation and Sustainability

The final theme synthesises insights from the preceding themes into actionable strategic directions for the PCDDP. These include hybrid revenue models, digital transformation roadmaps, capacity-building strategies, improved governance and stakeholder engagement, sustainability metrics and monitoring systems, and an innovation-oriented organisational culture. These strategic directions form the basis of Section 4.10 and are visually summarised in the conceptual model later introduced in Figure 16.

Together, these five themes provide a coherent analytical scaffolding for interpreting the PCDDP's sustainability trajectory. They also create a logical flow for the detailed thematic discussions presented in the sections that follow, ensuring a strong golden thread connecting the research questions, methodology and findings.

4.5 Theme 1: Drivers of Innovation and Sustainability

The first major theme emerging from the documentary analysis concerns the internal and external drivers that enable the PCDDP to pursue innovation and support long-term sustainability. These drivers reflect a combination of scientific capability, regulatory alignment, strategic partnerships, digital modernisation, and coherence with national and global research priorities. Collectively, they represent the platform's strongest levers for shaping its operational trajectory and positioning within South Africa's research infrastructure landscape.

Analysis of the coded dataset, particularly strategic plans, performance reviews, GLP inspection presentation reports to regulatory body SANAS and national policy frameworks, shows that innovation at the PCDDP is not a singular activity but a multi-dimensional process rooted in the interplay between human capital, advanced technological infrastructure, regulatory credibility and collaborative networks. These factors align closely with the patterns observed in comparable international research infrastructures and are consistent with the innovation drivers highlighted in Chapter 2.

4.5.1 Scientific and Technical Capability

Scientific and technical capability emerges as a central driver of innovation. Evidence from strategic documents and operational materials indicates that the PCDDP holds a distinguished position in the national research ecosystem owing to its GLP accreditation (enabling it to test drugs and vaccines in animals before they are tested in humans), advanced preclinical testing capabilities and specialised infrastructure, including BSL-2/3 facilities, behavioural animal models, and LCMS/MS analytical capacity. These capabilities enable the platform to offer services that are scarce within the Southern African region and position it as a credible partner for translational research.

Institutional records further demonstrate that these capabilities have been strengthened by investments in scientific instrumentation, digital quality-management systems, and ongoing professional development of technical staff. Such advancements reflect the principles of capability-driven innovation, where scientific expertise and infrastructure maturity form the foundation for service diversification, research excellence and industry collaboration.

4.5.2 Regulatory Accreditation and Quality Systems

Accreditation emerges as a second key innovation driver. The PCDDP's GLP certification and AAALAC accreditation ensures that its processes meet internationally recognised standards, which in turn enhances scientific credibility, client confidence and alignment with global regulatory expectations. Regulatory compliance also incentivises continuous improvement, as documented in SOP QA DOC11 and recurrent GLP inspection reports.

These quality-assurance mechanisms shape innovation by requiring validated methods, robust data integrity systems and standardised workflows. The shift toward digital systems (such as SimplerQMS) exemplifies innovation driven by regulatory expectations, where operational enhancements are motivated by compliance demands and inspection readiness.

4.5.3 Collaborative Networks and Knowledge Ecosystems

Partnerships with universities, industry, public-sector agencies and international organisations constitute another major driver of innovation. Performance-review documents, benchmarking reports and DST/DSI materials show that the PCDDP participates in multi-institutional research consortia, engages in joint training programmes, and contributes to vaccine-development and health-innovation initiatives.

This collaborative orientation is consistent with Open Innovation principles (Andriyani *et al.*, 2024), where knowledge flows, shared expertise and resource pooling enhance the scientific and operational capability of research infrastructures. The role of collaborative ecosystems in driving innovation is illustrated by comparative international models such as ELIXIR (Figure 11).

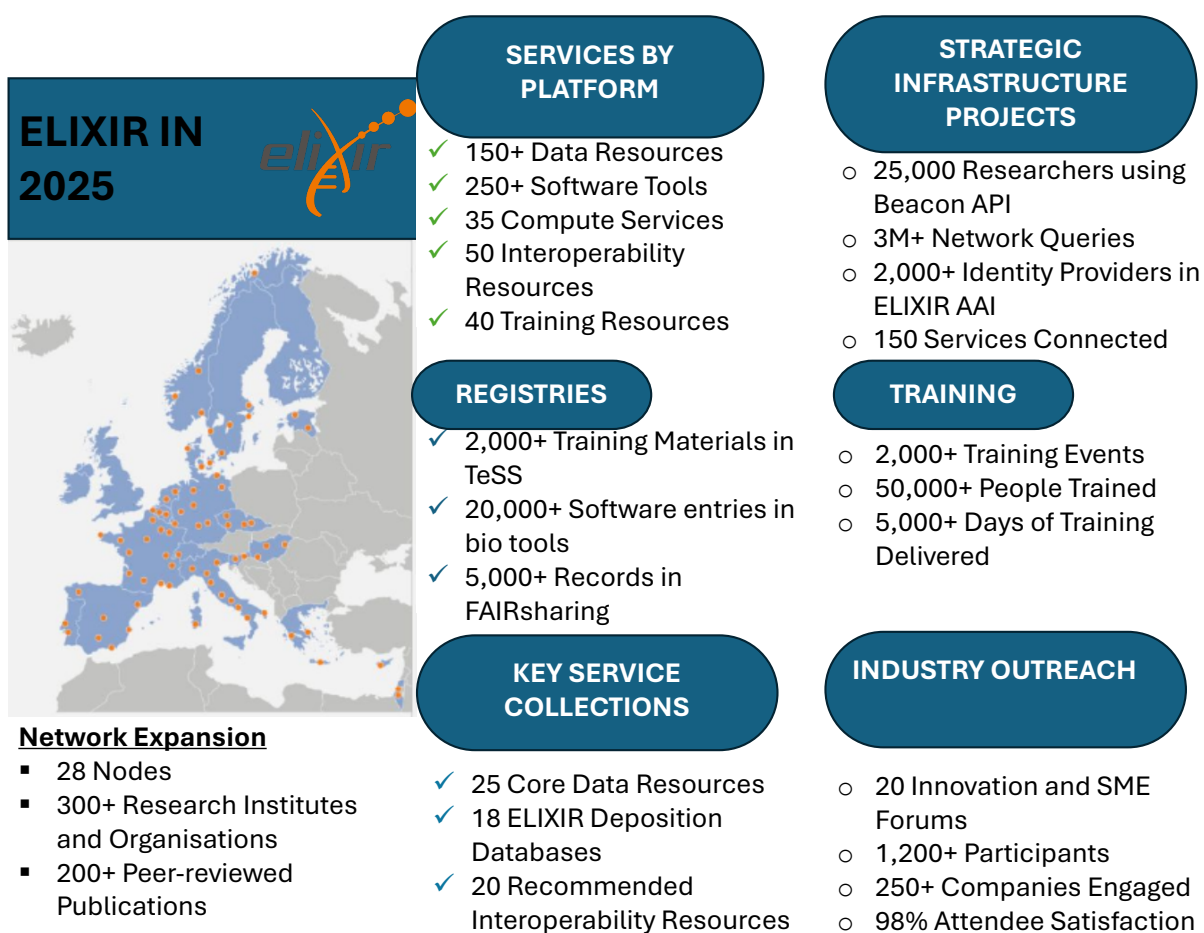


Figure 11: Overview of the ELIXIR infrastructure, showing distributed nodes, shared data services, training networks and integrated community structures (modified from Harrow *et al.*, 2021).

This model demonstrates how distributed governance, shared digital resources and collaborative communities collectively strengthen innovation capacity, a pattern reflected in the PCDDP's engagement with national consortia and global partners.

4.5.4 Alignment with International Data and Research Standards

Innovation at the PCDDP is also shaped by its alignment with international standards for data management and research integrity. FAIR (Findable, Accessible, Interoperable and Reusable) principles, often emphasised in global research-infrastructure policy (OECD, ELIXIR, ESFRI), offer a relevant benchmark for how digital and scientific processes should be structured (Figure 12).

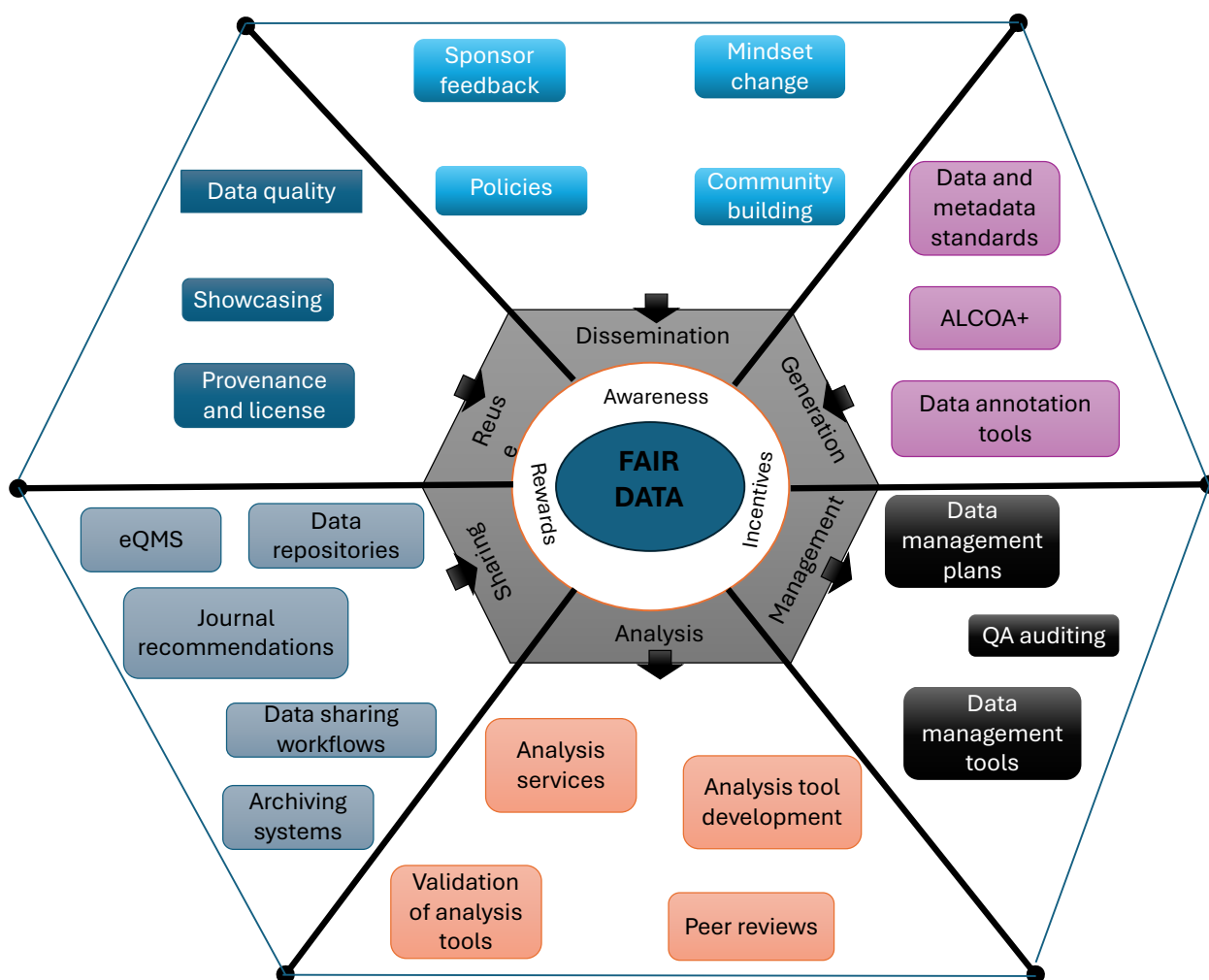


Figure 12: FAIR data model applied to life-science and preclinical research infrastructures (modified from Kemmer *et al.*, 2023).

The FAIR model complements the PCDDP's digital transformation efforts by highlighting how data accessibility, interoperability and reusability underpin research reproducibility, regulatory compliance and long-term scientific value. The alignment between FAIR principles and GLP-driven digital workflows underscores how global standards shape innovation agendas in research infrastructures.

4.5.5 Strategic Alignment with National STI Priorities

National policy documents, including the SARIR, DSI Strategic Plan, STI Decadal Plan and NRF strategies, repeatedly emphasise the need for research infrastructures to support socioeconomic development, pharmaceutical innovation, human capital development and health-related R&D. The PCDDP's strategic documents reflect clear alignment with these national priorities through its focus on translational drug development, vaccine research, postgraduate training, and partnership with national health-innovation consortia.

This alignment acts as an innovation driver by unlocking funding opportunities, enabling integration within national missions (such as pandemic preparedness and local biomanufacturing), and strengthening the platform's relevance within the national system of innovation.

4.5.6 Synthesis: Innovation as a Foundational Capability

Taken together, these drivers indicate that innovation at the PCDDP is anchored in capability, compliance, collaboration and strategic positioning. These drivers enable the platform to generate scientific value, diversify service offerings, strengthen national competitiveness and support broader policy goals. They also form the basis for understanding how innovation interacts with barriers, digital capabilities and international frameworks, as elaborated in subsequent sections of this chapter.

4.6 Theme 2: Barriers to Adopting Sustainable Strategies

The second major theme arising from the documentary analysis concerns the structural, operational and systemic barriers that constrain the PCDDP's ability to adopt sustainable strategies. While the platform has several strong innovation drivers, the coded data reveal persistent constraints related to infrastructure, funding, human capital, policy alignment and digital maturity. These barriers are not isolated challenges; rather, they form an interconnected set of pressures that collectively undermine the platform's long-term sustainability trajectory.

The analysis highlights that these constraints stem from both internal institutional conditions and broader features of South Africa's research and innovation system. They mirror many of the challenges reported in national policy documents, benchmarking exercises and global research-infrastructure assessments. Their cumulative effect is to limit the PCDDP's capacity to diversify revenue, expand service capabilities, and sustain quality and regulatory readiness over time.

4.6.1 Infrastructure Deficiencies and Legacy-System Dependency

Documentary evidence reveals that infrastructure limitations constitute one of the most persistent barriers. GLP inspection reports repeatedly note outdated or non-functional components of the Building Management System (BMS), limited spare-part availability, and the need for environmental-monitoring upgrades. This dependence on legacy systems increases operational risk, drives up maintenance costs, and reduces responsiveness to inspection requirements. These challenges directly affect regulatory compliance and diminish the agility required for service expansion and innovation.

Institutional records also note equipment reaching end of life, high replacement costs, and delays associated with procurement and importation. These material and technological constraints reduce the platform's ability to maintain state-of-the-art capabilities and meet industry expectations for competitive turnaround times.

4.6.2 Funding Instability and Financial Constraints

Funding dynamics emerge as a second critical barrier. Evidence across strategic documents and policy frameworks indicates that the PCDDP remains highly vulnerable to short-term, grant-dependent cycles. The absence of multi-year commitments restricts long-range planning, impedes strategic investment in infrastructure and digital systems, and limits the platform's ability to recruit or retain specialist personnel.

Broader system-level documents such as the NRF Strategic Plan and national research-funding analyses confirm that constrained public expenditure, currency risks and shifting government priorities pose continuing threats to the financial sustainability of research infrastructures. The platform's modest conversion rate from quotations to external income, as noted in institutional performance reviews, further illustrates the fragile nature of its revenue base.

4.6.3 Human-Capital Gaps and Operational Strain

Gaps in institutional capacity, staffing levels and digital skills were repeatedly identified in the coded data. Operational materials and review reports refer to limited staffing in key technical and administrative areas, dependence on a small number of highly skilled individuals, and pressures associated with regulatory reporting, quality-assurance processes and digital-system implementation.

These gaps constrain workflow efficiency, exacerbate risks of burnout, and reduce the organisation's ability to take on additional commercial or collaborative projects. Workforce limitations also undermine digital transformation efforts, since successful adoption of validated systems, standard operating procedures and data-integrity workflows requires a level of digital readiness that current staffing structures struggle to support.

4.6.4 Systemic Barriers: Policy, Regulatory Alignment and Institutional Fragmentation

The analysis also reveals systemic challenges across the wider national research-innovation landscape. Policy documents highlight fragmentation across departments, slow regulatory processes, and limited coordination between health, agriculture and science portfolios, all of which affect research infrastructures such as the PCDDP. Institutional records demonstrate difficulties engaging regulators, such as SAHPRA and DALRRD, limited visibility in national strategic platforms, and variable responsiveness to infrastructure prioritisation.

These systemic constraints impede strategic alignment, delay approvals, and reduce the platform's ability to position itself as a national node within mission-oriented health-innovation programmes. Fragmentation also contributes to inefficiencies in data governance, performance reporting and quality-assurance oversight.

4.6.5 Digital Maturity Constraints

Digital transformation is both an enabler and a barrier. While the PCDDP has begun transitioning toward validated digital systems such as SimplerQMS, documentary evidence highlights the continued reliance on manual processes, incomplete system integration, data-quality challenges and gaps in digital infrastructure. These constraints impede workflow optimisation, slow regulatory reporting, and limit the potential for data-driven cost modelling and performance analytics.

Digital-system costs, including licences, maintenance, and hardware upgrades, further contribute to financial strain. Without a comprehensive digital-maturity roadmap, the risks of under-utilised systems and inefficiencies remain high.

4.6.6 Limited Commercialisation Pathways and Industry Engagement

Performance-review documents and business-model assessments highlight a lack of structured commercialisation pathways, limited industry partnerships, and gaps in private-sector readiness to engage with preclinical testing platforms. The platform's existing client conversion rates point to challenges in market positioning, pricing strategy, contractual frameworks and stakeholder communication.

These barriers reduce the potential for diversified revenue streams and limit opportunities to co-develop new testing services, translational projects or partnership-driven innovations. Without systematic market engagement, the PCDDP remains constrained in shifting from grant dependency toward a more balanced hybrid model.

4.6.7 Synthesis: Barriers as Interlocking Constraints

The analysis shows that barriers to sustainability do not operate independently. Financial instability amplifies workforce constraints; infrastructure deficiencies worsen regulatory strain; digital-system gaps reinforce inefficiencies; and systemic fragmentation delays strategic alignment. Together, these interlocked constraints create a structural environment in which sustainable business-model innovation is difficult to achieve without coordinated reform and targeted investment.

These insights lay the foundation for the digital-capability analysis and international benchmarking presented in the subsequent sections of this chapter.

4.7 Theme 3: The Central Role of Digital Capabilities and Infrastructure

Digital capability emerges from the analysis as one of the most significant determinants of the PCDDP's long-term sustainability. Across institutional records, GLP inspection reports, quality-management documentation, and national policy frameworks, digital systems appear repeatedly as both an operational necessity and a strategic enabler. The coded dataset reflects a strong concentration of references to digitalisation, data tools, equipment management, operational

efficiency, financial strategy, and digital management, underscoring the centrality of technology to the platform's future viability.

Digital capabilities influence every dimension of the PCDDP's operating environment. They determine regulatory readiness, data integrity, workflow efficiency, cost containment, pricing accuracy, service scalability, and client responsiveness. The analysis also shows that digital capability is not synonymous with technological acquisition alone; rather, it requires integrated investment across processes, people, systems, and governance. The thematic findings indicate that the platform's digital trajectory operates across two interconnected layers, operational and strategic, which together shape its sustainability pathway.

The figure below (Figure 13) illustrates these two layers of digital capability and their relationship to operational efficiency and strategic sustainability outcomes.

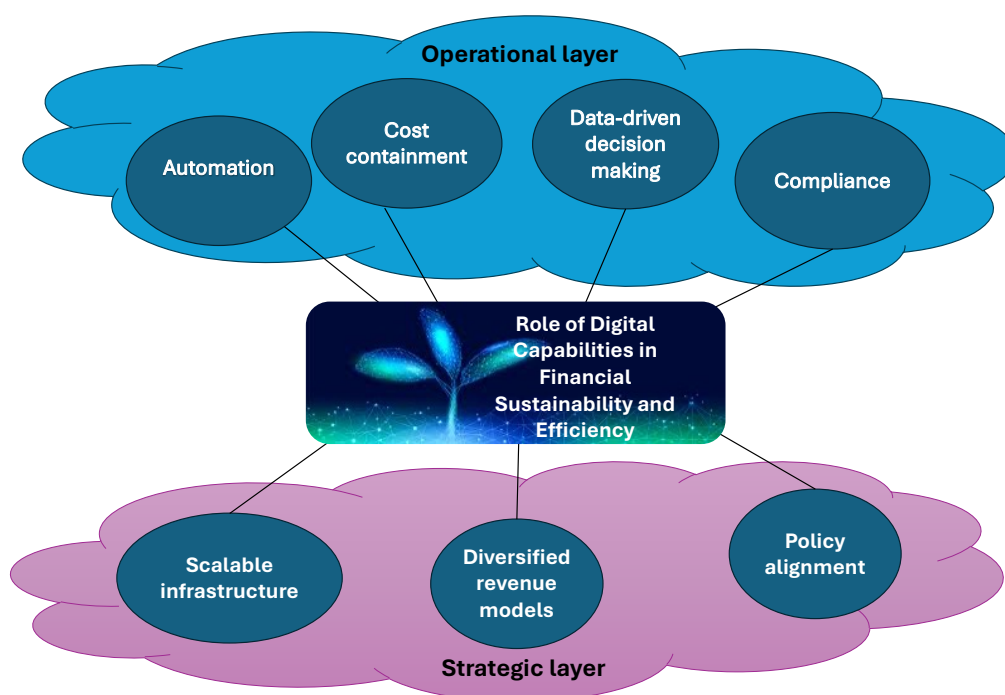


Figure 13: Digital capabilities underpin both operational efficiency and strategic sustainability, showing the interaction between day-to-day digital processes and long-term strategic systems.

4.7.1 Scalable Digital Infrastructure

The documentary evidence shows that scalable digital infrastructure is becoming foundational to the PCDDP's operational integrity. Records relating to the transition from paper-based procedures to the SimplerQMS system demonstrate the importance of validated data systems for compliance with GLP requirements. The installation of upgraded building-management and environmental-monitoring systems further reflects a shift toward real-time oversight, automated alerts, and centralised data capture.

Such upgrades support regulatory audit readiness, enhance traceability, reduce error rates, and provide a foundation for cost-effective expansion of service offerings (Harrow *et al.*, 2021; Kemmer *et al.*, 2023). However, transitioning to a fully digital infrastructure also introduces lifecycle costs related to licensing, validation, training, and maintenance, costs that must be explicitly built into future pricing and financial planning models.

4.7.2 Operational Efficiency through Automation and Data Integrity

Digital systems directly support operational efficiency across multiple workflows, including study documentation, SOP management, equipment monitoring, record-keeping, and billing pathways. Documents on the transition to electronic QMS protocols show reduced administrative overhead, fewer manual inconsistencies, and quicker document turnaround times.

GLP inspection records referencing potential remote inspections and electronic data transmission with international clients indicate that adherence to validated digital systems enhances PCDDP's competitiveness and credibility. The analysis shows that automation is most effective when supported by clear SOPs, trained personnel, and regular data-quality checks, ensuring that workflow optimisation translates into measurable efficiency gains. This observation is supported by other studies such as Fagbore *et al.* (2022:241) and Julião *et al.* (2025).

4.7.3 Workforce Readiness and Digital-Capability Maturity

The coded data strongly emphasise the role of human capital in determining the success of digital transformation (Vong *et al.*, 2025). While technology acquisition is progressing, the documentary evidence highlights gaps in digital literacy, limited staff capacity to manage new systems, and uneven readiness for workflow digitisation.

Documents referencing operational strain and capacity constraints indicate that digital adoption will not be fully realised without structured training, change-management processes, and ongoing technical support. The analysis therefore positions workforce development as an essential complement to digital investments, with digital-capability maturity contingent upon skills, leadership engagement, and organisational culture (Vong *et al.*, 2025)

4.7.4 Strategic Alignment and Long-Term Digital Planning

Digital capability is also a strategic asset (Alrub & Sánchez-Cañizares, 2025; Prakasa & Jumani, 2024). National policy documents such as the DSI Strategic Plan and NRF digital-transformation frameworks emphasise the importance of digital systems for impact reporting, performance monitoring, and alignment with global science-governance standards. The PCDDP's digital investments, particularly in validated QMS systems, integrated infrastructure monitoring, and digital

workflow tools, thus position the platform to align with national expectations for accountability, transparency, and research-infrastructure modernisation.

However, the analysis shows a need for a more formalised digital-transformation roadmap that integrates lifecycle costing, KPI monitoring, data governance, training, and system interoperability. Without such a roadmap, digital investments risk remaining fragmented and under-leveraged.

4.7.5 Synthesis: Digital Capability as a Cross-Cutting Enabler

Digital capability acts as a cross-cutting enabler that strengthens the platform's resilience across all sustainability domains. It improves regulatory compliance, enhances cost control, enables data-driven decision-making, strengthens financial sustainability, improves market competitiveness, and supports expanded service offerings (Chen & Wang, 2024; Kong *et al.*, 2025). The document evidence shows that while PCDDP has made substantive progress, its digital transformation remains incomplete and requires strategic investment to reach full maturity.

This theme provides a bridge to the international benchmarking analysis in the next section, which demonstrates how leading research infrastructures leverage digital capability as a core foundation of sustainable business-model design.

4.8 Theme 4: International Best Practices Relevant to Research Infrastructures

The analysis of international policy documents, benchmarking reports, and global research-infrastructure models reveals several practices that hold strong relevance for the PCDDP. These practices reflect mature systems of governance, digital readiness, distributed service models, interoperability, and sustained investment mechanisms that enable research infrastructures in high-performing countries to achieve long-term sustainability (OECD, 2025). The thematic codes relating to collaboration, governance innovation, best practices, research impact, access optimisation and research entrepreneurship highlight a consistent set of international patterns that can guide the PCDDP's strategic direction.

Although the South African context differs in terms of resource availability, regulatory constraints and market dynamics, the benchmarking evidence demonstrates that selected global approaches are adaptable. International infrastructures emphasise distributed networks, open-access frameworks, industry-academia integration, dual-use operating models, and structured capability development. These principles align closely with the challenges and opportunities identified earlier in the chapter.

The first figure introduced below (Figure 14) illustrates a widely used international research-infrastructure model and serves as the main discussion that follows in 4.8.1.

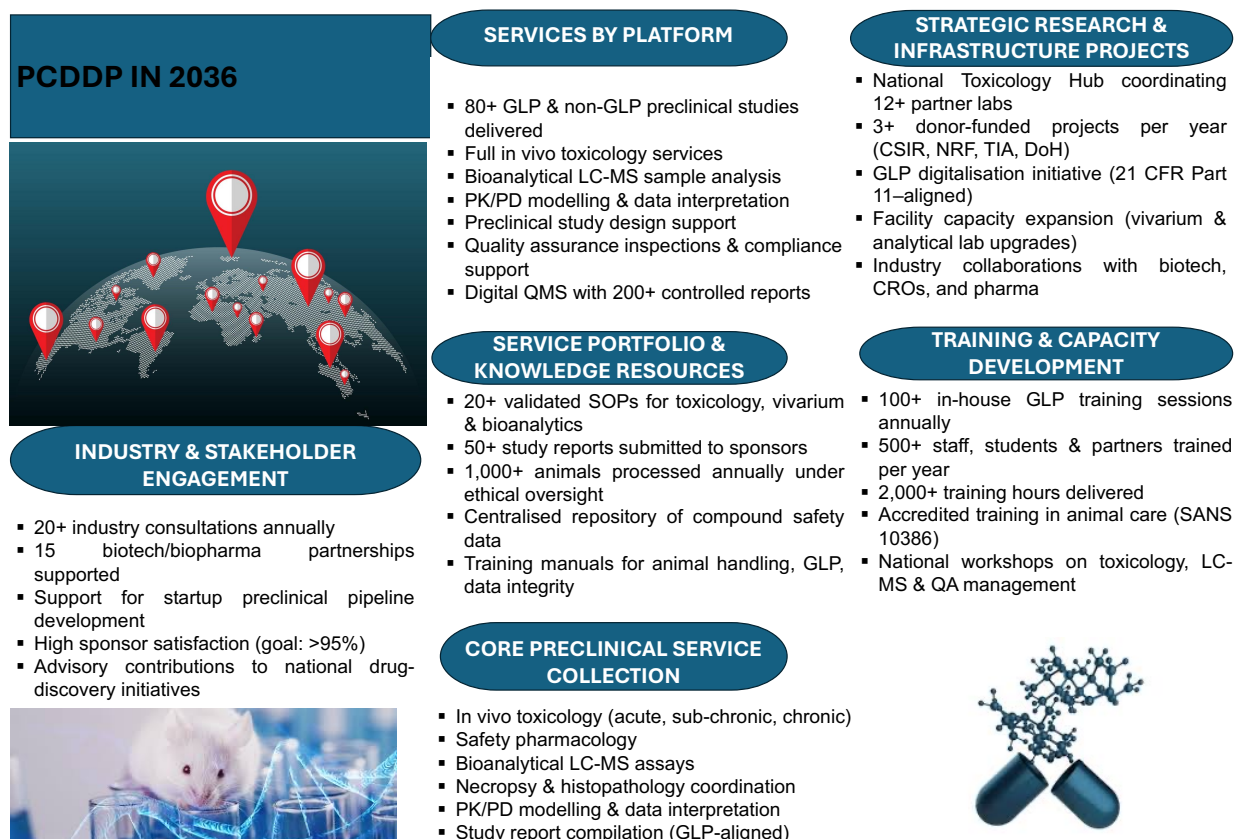


Figure 14: Overview of the Preclinical Drug Development Platform (PCDDP) service ecosystem and infrastructure for 2036 (Overview of the ELIXIR infrastructure was adapted to align conceptually with PCDDP's context)

4.8.1 International Collaboration and Distributed Infrastructure Models

A central pattern observed internationally is the reliance on distributed infrastructure networks. Platforms such as ELIXIR in Europe, the European Molecular Biology Laboratory (EMBL), and the Max Planck Society's research nodes illustrate how research infrastructures can pool expertise, technology and data across multiple centres while retaining strong coordinated governance (Reiner *et al.*, 2017:1730; Thakur *et al.*, 2023:D10). These distributed models enable shared access to high-cost research equipment, regional specialisation without duplication, standardised operating procedures, interoperability across laboratories and scalability of service provision.

The PCDDP's existing partnerships with national universities and international networks such as CEPI and the WHO mRNA platform demonstrate early alignment with this model; however, the benchmarking evidence indicates that more formalised and structured integration would enhance sustainability.

4.8.2 Open Science, FAIR Data, and Digital Interoperability

Open-science principles, including open access to research outputs, open data models, and interoperable digital infrastructures, were consistently highlighted in global best-practice documents. These principles are underpinned by the FAIR framework (findable, accessible,

interoperable, reusable), which is now embedded in European and OECD-aligned research infrastructure policy (Kemmer *et al.*, 2023; de Groot *et al.*, 2024).

The second figure below illustrates a FAIR-aligned data lifecycle, contextualised for preclinical research environments (Figure 15). The model shows the flow of data from generation through management, analysis, reporting, and archiving, highlighting the supporting systems such as eQMS and the use of validated tools, governance structures such as Study Director oversight, Quality Assurance auditing and cultural elements.

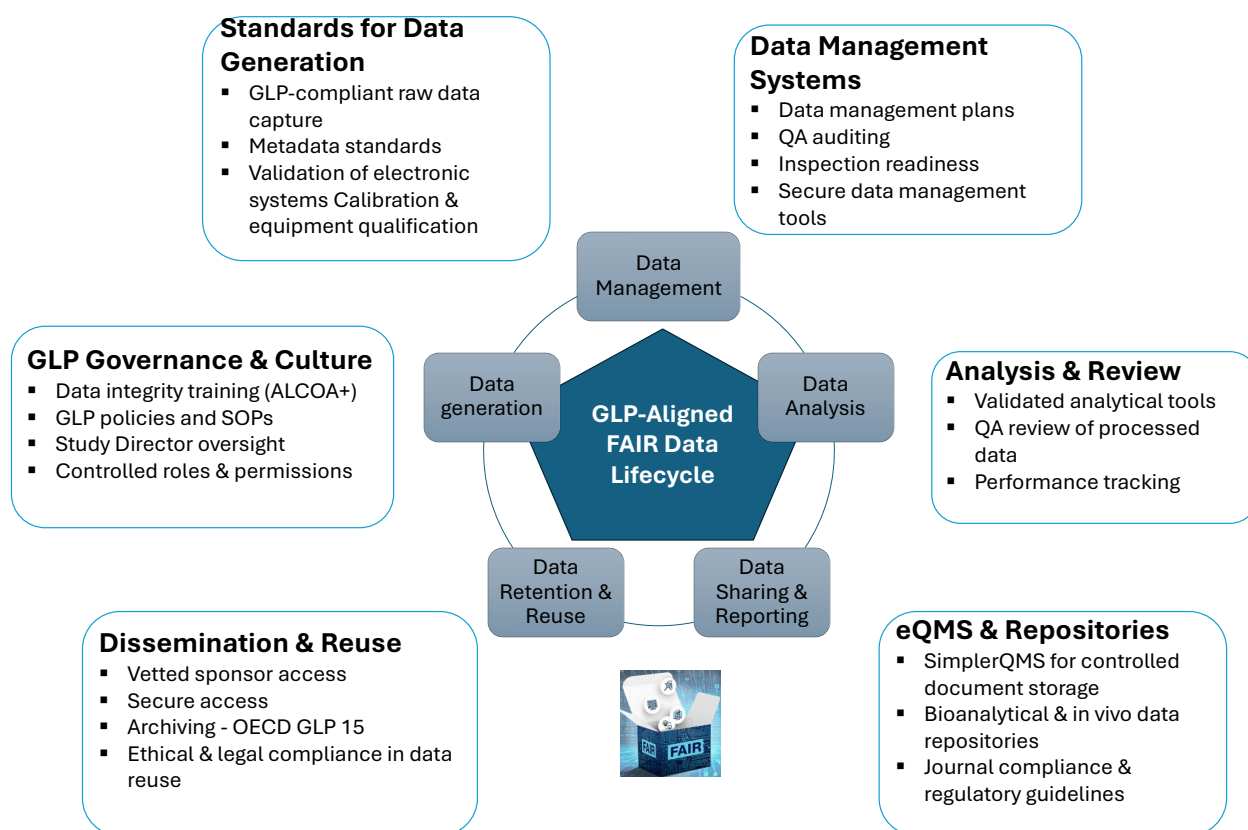


Figure 15: FAIR data lifecycle adapted for linked to GLP-aligned data-integrity requirements relevant to the PCDDP.

FAIR data approaches strengthen research infrastructures by improving data traceability and quality, regulatory audit readiness, cross-institutional collaboration, opportunities for computational and AI-driven research and transparency in public research investment (Harrow *et al.*, 2021; Kemmer *et al.*, 2023):

The analysis of PCDDP documentation shows growing alignment through digitalisation efforts such as SimplerQMS adoption; however, a more explicit FAIR-aligned data governance plan would position the platform to engage more effectively with international partners and form collaborations with other research institutes.

Governance Innovation and Stakeholder Integration

International models place significant emphasis on collaborative governance (Kolar *et al.*, 2023). This includes representation from government, academia, funders, industry, regulators, and public-interest groups. The rationale is that research infrastructures operate with different mandates such as offering public value, scientific advancement and commercial application, and therefore require shared oversight (Wood *et al.*, 2013; OECD, 2023; OECD, 205). The analysis highlights several governance practices that could be adapted for PCDDP establishing advisory boards with multi-sector representation, adopting transparent access and pricing frameworks, aligning oversight mechanisms with national strategic priorities, implementing regular performance evaluation cycles and most importantly incorporating stakeholder engagement strategies such as digital forums, open days, and consortium meetings. This aligns strongly with South Africa's SARIR framework and with observations from OECD (2019–2023) on long-term viability for national research infrastructures.

Dual-Use and Hybrid Service Models

Many leading research infrastructures operate dual-use models, providing both public-value research services (open access, capacity building, regulatory scientific support), and market-driven commercial services (contract research, specialised testing, consultancy, industry partnerships) (Reiner *et al.*, 2017:1730; Kolar *et al.*, 2023; Thakur *et al.*, 2023:D10). This hybrid approach improves financial resilience and enhances the infrastructure's strategic relevance. International CROs and scientific infrastructures such as EMBL-EBI, the Karolinska preclinical facilities, and Singapore's A*STAR institutes (Reiner *et al.*, 2017:1730; Thakur *et al.*, 2023:D10), demonstrate that hybrid models enable revenue diversification, greater autonomy from annual grant cycles, targeted industry collaborations and increased global visibility.

The PCDDP's existing blend of GLP testing, postgraduate training and research collaboration indicates early movement toward this model, but the analysis shows significant potential for expansion.

Capacity-Building Systems and Global Competency Alignment

International infrastructures invest significantly in workforce development, standardised training, and competency accreditation. Examples include, ELIXIR's cross-node training programmes (Harrow *et al.*, 2021), FELASA and AAALAC accreditation pathways (Newcomer & Cloutier, 2018; Gyger *et al.*, 2019:137) and ESFRI-aligned capacity-development frameworks (Kolar *et al.*, 2023). The PCDDP's training outputs of MSc and PhD supervision and internal GLP training, are consistent with these models; however, benchmarking shows that international infrastructures often scale training into revenue-generating specialist courses, certification programmes, and global workshops (Newcomer & Cloutier, 2018; Gyger *et al.*, 2019:137). This constitutes a viable expansion path for PCDDP.

4.8.6 Synthesis: Implications for PCDDP

The benchmarking evidence indicates that adopting selected international best practices would strengthen PCDDP's sustainability, including:

- adopting distributed-network collaboration models
- embedding FAIR-aligned data governance
- formalising cross-sector governance bodies
- expanding dual-use commercial/regulatory offerings
- building structured international training programmes
- aligning digital systems with global interoperability standards

Collectively, these practices would support the platform's transition from a predominantly grant-dependent infrastructure toward a more resilient, innovation-oriented, globally connected research environment (Reiner *et al.*, 2017:1730; Thakur *et al.*, 2023:D10).

4.9 Theme 5: Strategic Recommendations for Integrating Innovation and Sustainability

The final theme presents the strategic recommendations emerging from the documentary evidence and the coded dataset. These recommendations respond directly to the structural constraints, operational pressures, digital gaps, capability limitations, and governance challenges identified earlier in the analysis. They also draw on the opportunities illuminated in Theme 1 and the global best practices identified in Theme 4. Taken together, the recommendations outline the components of a sustainability-oriented business model for the PCDDP and comparable South African research infrastructures.

Across the coded materials, five strategic domains consistently emerged as essential to strengthening long-term sustainability and these are:

- (1) hybrid revenue generation and business-model restructuring,
- (2) digital transformation and data-governance modernisation,
- (3) capacity development and workforce capability,
- (4) governance, stakeholder engagement and policy alignment, and
- (5) sustainability metrics and continuous improvement.

These domains form the strategic enablers that allow the PCDDP to progress beyond a grant-dependent operating model, better manage technological and regulatory complexity, and align with international standards for mature research infrastructures.

The overall logic of this transition is captured in the figure below (Figure 16).

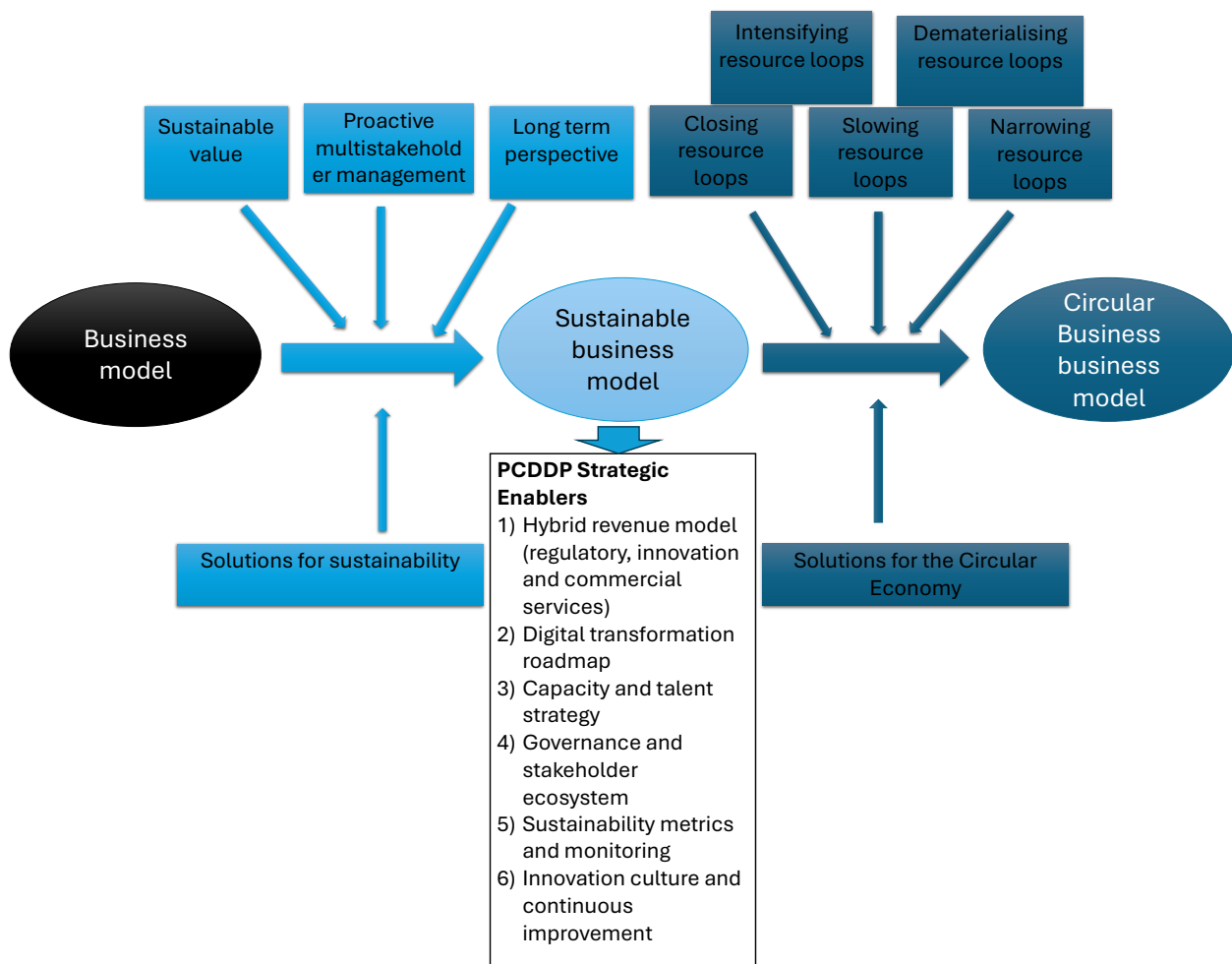


Figure 16: The PCDDP Business Model Transformation Pathway, illustrating the progression from a traditional regulatory testing model toward a sustainable and ultimately circular operating logic.

4.9.1 Hybrid Revenue Model and Business-Model Diversification

The coded dataset illustrates that the PCDDP remains heavily dependent on cyclical public funding, supplemented by irregular external income that fluctuates with quotation conversion rates. The documents point toward a clear need to diversify revenue sources, not by abandoning the regulatory mission but by expanding commercial testing services, contract research, and innovation partnerships.

A hybrid model, combining regulatory testing, postgraduate training, commercial service provision and collaborative R&D, mirrors international best practices and offers several advantages such as reduced vulnerability to grant discontinuities, improved cash-flow predictability through fee-based services, stronger relationships with industry and translational actors and enhanced visibility within regional innovation ecosystems (Harrow *et al.*, 2021; Jun *et al.*, 2021). The business model revision noted in the 2022 and 2024 performance documents provides the starting point, but further refinement is needed to ensure accurate costing, value-based pricing, market segmentation, and formalised service-level agreements.

Digital Transformation Roadmap and Data-Integrity Systems

Digital transformation emerges as the most important enabler for operational efficiency and regulatory robustness (Vărzaru & Bocean, 2024; Held *et al.*, 2025). The transition from paper-based procedures to SimplerQMS, the planned improvements to the BMS, and the need for integrated data workflows represent foundational steps toward digital maturity. To strengthen sustainability, the digital transformation roadmap should, embed validated electronic systems across all study processes, integrate financial, operational and instrument-tracking systems, support remote audits, virtual inspections, and digital client interfaces, align data governance with FAIR principles and more importantly reduce operational costs through automation and quality optimisation (Harrow *et al.*, 2021; Jun *et al.*, 2021; Thakur *et al.*, 2023:D10).

This aligns with international models where digital maturity is strongly associated with improved efficiency, reduced compliance risk, and enhanced global competitiveness (Harrow *et al.*, 2021; Vărzaru & Bocean, 2024; Held *et al.*, 2025).

Capacity and Talent Development

The documents highlight that sustainability is increasingly constrained by both staffing shortages and skill-specific gaps, particularly in digital capability, regulatory science, commercial engagement, and data analytics. Workforce readiness is therefore a strategic determinant of sustainability (Vong *et al.*, 2025). A structured capacity-development strategy should include targeted training in GLP digital systems and data-integrity requirements, the establishment of a skills pipeline through postgraduate training, strategic hiring in key technical and business-model areas and leveraging international partners for specialised training programmes (Koler *et al.*, 2023; Vong *et al.*, 2025).

Institutional support from the NWU Faculty of Health Sciences, together with external partnerships such as SAMVAC and CEPI, create meaningful opportunities for strengthening human capital for PCDDP.

4.9.4 Governance Architecture and Stakeholder Ecosystem Development

The analysis shows that PCDDP's sustainability is affected by fragmented engagement with regulators, irregular industry involvement, and limited integration into national governance frameworks. A governance architecture that systematically incorporates industry, funders, regulators, academic partners and policy actors is therefore essential (Vince *et al.*, 2024:381).

This approach would without a doubt facilitate strategic alignment with national health-innovation mandates, enable a smoother regulatory engagement and reduced approval delays, increase opportunities for coordinated fundraising and PPP development, increase legitimacy and transparency in pricing, access and service decisions and increase more cohesive planning across the national research infrastructure landscape (Koler *et al.*, 2023).

The significance of an expanded governance ecosystem is illustrated in the thematic cluster summary below in Figure 10.

Sustainability Metrics, Monitoring and Continuous Improvement

The final strategic domain concerns impact measurement and ongoing learning. Consistent with SARIR and OECD guidance, the PCDDP requires a suite of sustainability indicators that monitor financial performance, technical capability, infrastructure utilisation, client engagement, regulatory readiness, and research outputs. These indicators should be linked to annual reporting cycles, digital dashboards, business-model refinement, and also long-term planning for equipment renewal and skill development (Farida & Setiawan, 2022; Handoyo *et al.*, 2023). A structured monitoring system enables early identification of emerging constraints, supports evidence-based decision-making, and reinforces the platform's accountability to funders and partners (Farida & Setiawan, 2022; Handoyo *et al.*, 2023; Najjar & Qandeel, 2025).

Integrated Conceptual View of Strategic Recommendations

The interaction between the five strategic domains is synthesised in the conceptual model below (Figure 17).

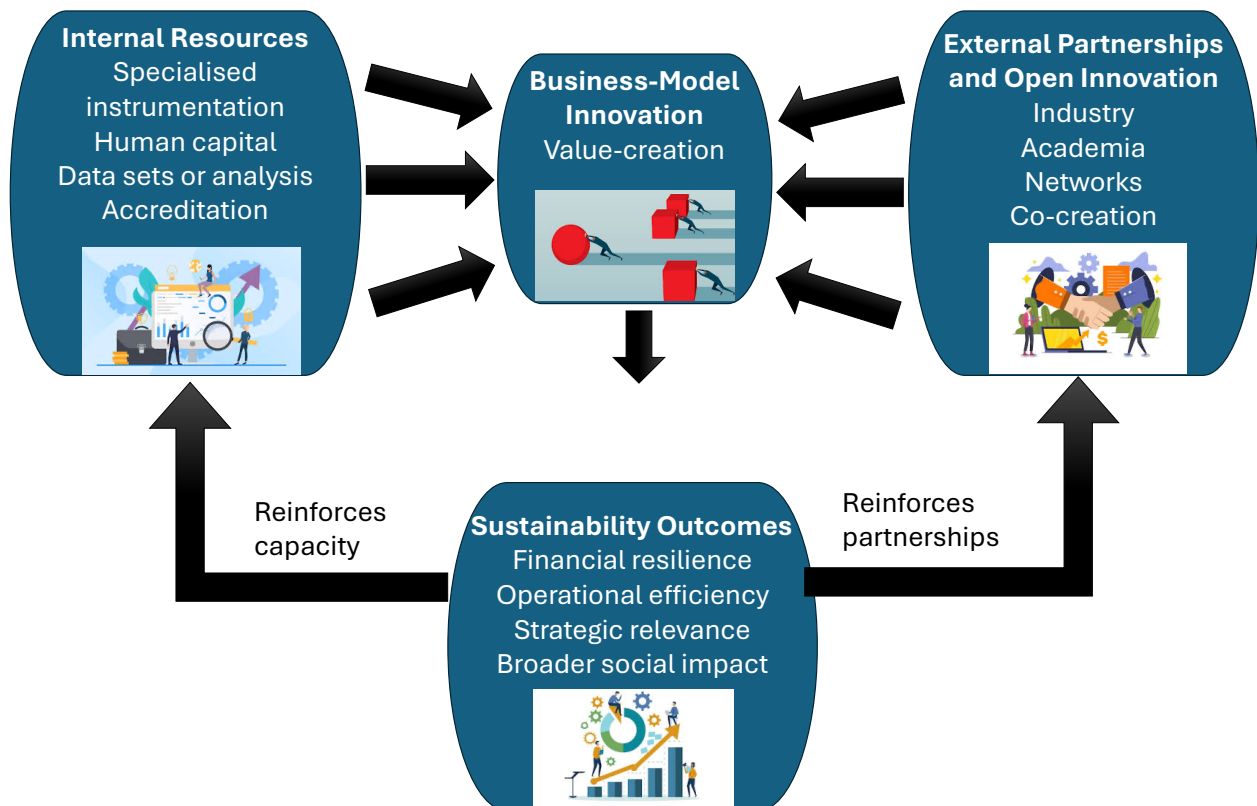


Figure 17: Conceptual model illustrating how the five strategic domains, innovation drivers, digital capabilities, sustainability mechanisms, international best practices, and barriers, interact to shape the PCDDP's sustainability trajectory.

4.10 Integrated Interpretation: Applying the RBV-OI-BMI Framework to the Empirical Findings

This section synthesised the thematic findings presented in Sections 4.3 to 4.9 by interpreting them through the integrated conceptual framework developed in Chapter 2. The framework combined the RBV, OI, and BMI to provide a coherent explanation of how the PCDDP's sustainability dynamics emerge from the interaction between internal capabilities, collaborative networks, and business model structures. This integrated interpretation aligns with the study's abductive and critical realist orientation by connecting observable patterns in the documentary evidence to the underlying generative mechanisms that shape organisational outcomes.

4.10.1 RBV Interpretation: Internal Capabilities and Their Constraints

The findings from the document analysis demonstrate that the PCDDP possesses a distinctive combination of tangible and intangible capabilities that align closely with the Resource-Based View's understanding of organisational advantage. These capabilities underpin the platform's strategic importance within South Africa's research infrastructure landscape. However, the evidence also shows that these capabilities remain vulnerable in the absence of continued investment, supportive governance structures, and operational autonomy.

Across institutional documentation, including the SANAS GLP Inspection Reports (2021–2025) *and the original* PCDDP Business Plan (2011), the PCDDP's physical infrastructure emerges as a central strength. The platform's GLP-compliant laboratories, which are repeatedly emphasised as nationally scarce resource facility, form the basis of its value proposition. The presence of AAALAC-aligned animal facilities validated scientific instruments such as LCMS/MS analytical systems, and biosafety level 2 and 3 environments positions the platform to conduct complex preclinical studies at internationally recognised standards.

These capabilities were reflected in several codes related to infrastructure, advanced technology, operational efficiency, *and* research and development (discussed in Sections 4.4 to 4.9). The documents show that the PCDDP's infrastructure allows it to support diverse scientific activities, from toxicology testing to vaccine research. This aligns with RBV's emphasis on the strategic significance of assets that are valuable, rare, and difficult to imitate.

However, the same documents also highlight structural pressures on these tangible assets. Presentations on the platform's future growth, submitted to the DSI (2025), note that several high-end instruments are approaching the end of their operational life cycles, with replacement costs estimated at over R140 million. The legacy Building Management System (BMS), previously critical for environmental monitoring and regulatory compliance, had become non-functional due to the

unavailability of spare components. Procurement delays described consistently across multiple internal reports, further hinder timely equipment servicing and renewal. These constraints directly weaken the long-term VRIN potential of the platform's infrastructure, as the inability to maintain or replace key assets jeopardises both operational reliability and compliance standing.

4.10.1.2 Intangible Capabilities: Expertise, Accreditation, and Organisational Reputation

The document analysis also highlights several intangible capabilities that contribute to the PCDDP's institutional strength. The platform's longstanding GLP accreditation serves as a core reputational asset, identified in the GLP inspection reports as a marker of credibility recognised by national and international partners. This accreditation requires highly specialised human capital, including study directors, regulatory specialists and animal facility technicians, whose expertise underpins GLP compliance.

Institutional reputation has been enhanced by partnerships with organisations such as CEPI, the Gates Foundation, and the Czech Centre for Phenogenomics. The PCDDP's contribution to postgraduate training, having supported 32 MSc and 7 PhD candidates and produced 54 publications since 2016, further reinforces its status as a national centre of excellence. Yet these intangible capabilities are also fragile. Documents reveal concerns regarding high turnover risk in critical regulatory and technical roles, with limited succession planning and career progression pathways for specialised staff. The platform remains dependent on a small number of senior scientists whose departure would significantly disrupt operations. From an RBV perspective, the rarity and inimitability of these skills enhance the organisation's advantage, but their vulnerability undermines the ability to sustain this advantage over time.

4.10.1.3 Operational Capability Maturity

Operational capability reflected in internal systems, routines, and organisational processes, emerged as a third capability layer. The transition to SimplerQMS, evidenced by SOP QA DOC11, marks a shift toward more efficient and digitally supported quality management. This change enhances traceability, inspection readiness and long-term data integrity, all of which are critical for GLP environments (Timóteo *et al.*, 2021).

However, multiple internal reports highlight operational constraints linked to NWU's centralised procurement and budget control mechanisms. These processes introduce delays in purchasing consumables, contracting maintenance services and approving routine operational expenditures. Although operational systems such as SOPs, eQMS workflows and scheduling routines are strong, their effectiveness is diminished by dependencies on administrative structures outside the facility's control.

4.10.1.4 Interpretation: RBV Perspective on Capability Strength and Fragility

Taken together, the empirical findings show that the PCDDP holds valuable, rare and institutionally embedded capabilities that strongly align with RBV's definition of strategic advantage. The platform's scientific infrastructure, accreditation status, expert human capital, and operational routines constitute a sophisticated capability base that is not easily replicated elsewhere in South Africa.

However, RBV also emphasises that sustained advantage requires continuous renewal. The documents reveal that the PCDDP's capabilities, though strong, are susceptible to decline due to funding instability, aging equipment, skill shortages and administrative dependencies. In RBV terms, the platform's resources are valuable and rare, but their sustainability is undermined by constraints that limit effective utilisation, renewal, and long-term leverage.

The PCDDP therefore demonstrates both notable organisational strengths and structural fragilities. These dynamics provide important context for the subsequent analysis of external pressures, collaborative networks and business model adaptation presented in later subsections.

4.10.2 OI Interpretation: Collaboration as a Mechanism for Capability Extension

The documentary analysis shows that collaboration is central to how the PCDDP compensates for internal capability gaps, expands its scientific reach, and sustains its operational relevance within the national and international research ecosystem. From an Open Innovation perspective, the organisation operates as a knowledge-intermediary embedded in a dynamic network of academic partners, industry actors, government agencies and global scientific institutions. The documents reveal that both inbound and outbound knowledge flows are critical to the organisation's ability to maintain GLP compliance, broaden its service offerings and respond to emerging research priorities.

4.10.2.1 Inbound Knowledge Flows: Reinforcing Scientific and Regulatory Competencies

Several internal and external documents highlight the extent to which the PCDDP depends on external expertise to strengthen its technical and regulatory capabilities. Internal presentations and benchmarking reports describe collaborations with the Central University of Technology, Pharmacen and Conoche Biotech, which supported method development, equipment validation and specialised analyses. The South African mRNA Vaccine Consortium (SAMVAC) provided advanced methodological support for vaccine-related studies, while international institutions such as the Czech Centre for Phenogenomics facilitated access to sophisticated CRISPR techniques.

The COVID-19 period illustrated the importance of inbound knowledge flows, with partners such as Corteva providing remote support during GLP inspections, demonstrating the organisation's reliance on external networks to maintain compliance in the absence of internal redundancy.

These activities were reflected prominently in codes relating to *collaboration*, *advanced technology*, *external expertise* and *research capability building*. Additionally, these inbound flows mitigate capability gaps linked to staff shortages, aging infrastructure and limited in-house methodological diversity. They also reflect OI's core premise that knowledge essential for innovation resides beyond organisational boundaries and must be accessed through active collaboration (Aquilani *et al.*, 2020).

4.10.2.2 Outbound Knowledge Flows: Dissemination, Capacity Development and Scientific Visibility

Outbound knowledge flows were equally prominent across the coded documents. The PCDDP plays a recognised role as a national capacity-building hub, providing GLP training to postgraduate students and early-career scientists, as documented in the platform's Portfolio of Evidence. The 54 peer-reviewed publications generated since 2016, along with supervision of 32 MSc and seven PhD candidates, highlight the platform's contribution to scientific knowledge production.

Institutional presentations reveal multiple instances where the PCDDP provided advisory support to organisations such as Afrigen, UCT and international partners engaged in vaccine and biologics development. The platform also contributes to policy-facing dissemination through DSI reviews, stakeholder briefings and technical reporting. These outbound flows reinforce the PCDDP's legitimacy and position it as a conduit between laboratory-based science and the wider innovation system, therefore aligning closely with OI's emphasis on knowledge dissemination as a source of collective value creation.

4.10.2.3 Industry and Public Sector Linkages: Emerging but Constrained Engagement

The documents show evidence of expanding engagement with industry, although at levels still below those observed in international research infrastructures. The Performance Portfolio for 2022 records twenty quotations issued to private-sector clients for preclinical services, indicating growing interest from biotechnology firms, pharmaceutical developers and contract research organisations. Additional evidence of engagement includes pilot studies with emerging biotech companies and advisory interactions with regulatory consultants. Public-sector linkages are stronger and more consistent. The PCDDP aligns closely with instruments such as the STI Decadal Plan, both of which position research infrastructures as strategic enablers of national health innovation. The documents suggest that these relationships reinforce the platform's strategic relevance but provide limited financial or operational stability.

Thematic coding revealed persistent constraints affecting both sectors, including procurement delays, limited commercial readiness in the domestic biotech industry, and administrative processes that impede responsiveness to potential partners. This supports the OI argument that collaborations depend not only on willingness but also on the systemic environment that enables or restricts cross-boundary exchange.

4.10.2.4 Structural Dependencies and Absorptive Capacity Limitations

OI theory highlights that innovation benefits depend on the organisation's ability to absorb, integrate and exploit incoming knowledge (Arsanti *et al.*, 2024). Several constraints identified in the document analysis weaken the PCDDP's absorptive capacity and these include:

- Digital infrastructure gaps hinder the seamless exchange of data, regulatory documentation and experimental records, particularly relevant given the GLP reliance on electronic traceability.
- Staff time constraints, particularly for senior regulatory and scientific personnel, limit participation in collaborative research and international projects.
- Fragmentation within the South African National System of Innovation, noted in NSTF (2024) analyses, creates inconsistencies in support, coordination and strategic alignment across institutions.
- Administrative rigidity, especially in procurement and contracting, limits the organisation's ability to respond quickly to external opportunities.

These systemic dependencies mean that collaboration, while essential, does not always translate into expanded capability or improved sustainability. Instead, it can create additional pressure when internal systems cannot effectively support or integrate partnership activities.

4.10.3 BMI Interpretation: Business Model Adaptation Under Structural Constraint

The BMI lens provides a useful interpretive perspective for understanding how the PCDDP seeks to reconfigure its value creation, value delivery and value capture mechanisms in response to internal capability strengths (as discussed under RBV) and systemic constraints (Section 4.4). The analysis demonstrates that the platform is actively engaged in incremental forms of business model adaptation yet remains structurally inhibited from achieving deeper or more transformative business model redesign. The documentary evidence consistently reveals attempts to evolve the organisation's service architecture, operational routines and strategic positioning; however, these efforts occur within an environment characterised by limited autonomy, administrative rigidity and resource scarcity.

Evolution of the Value Proposition

Internal business model reviews (2024-2025), SANAS inspection materials and strategic documents show a slow but deliberate broadening of the PCDDP's value proposition. Several examples listed below illustrate this evolution of PCDDP and these include the expansion of GLP-compliant study offerings in the Documents such as the SANAS GLP Inspection Reports (2021-2025) and Future Growth of PCDDP Presentation to DSI (2025) describe the introduction of new study types, including vaccine-related evaluations, extended toxicology pipelines and exploratory biologics research. Also increased emphasis on training and advisory services in The Portfolio of Evidence highlights the platform's role in providing specialist GLP training to postgraduate students and regulatory advisory support to external partners such as Afrigen, UCT and the SAMVAC consortium. Lastly the strategic pursuit of a virtual toxicity hub evidenced in The 2025 strategic presentation communicates the intention to leverage digital systems to support remote monitoring, document control and inter-institutional collaboration, an embryonic shift towards a digitally enabled service model.

These developments demonstrate incremental BMI, reflecting an organisation responding to emerging scientific opportunities while seeking to stabilise and diversify its service portfolio.

Operational Barriers to Business Model Innovation

Despite the strategic intent evident in internal documents, the operational environment constrains the scope for business model redesign. Several barriers are repeatedly highlighted, and these include the restricted financial and operational autonomy observed in the documents that emphasise that the PCDDP cannot freely allocate or reinvest income from contract research. Key decisions remain embedded within NWU's centralised financial systems, limiting the agility required to pursue new opportunities or reinvest in critical infrastructure. More importantly, the procurement delays evidenced in the Internal assessments flag chronic delays in equipment procurement and consumable acquisition, which lead to workflow disruptions, extended turnaround times and reduced client confidence (coded as *material and technology challenges* and *systemic challenges*) is another challenge.

Incomplete integration of digital systems such as SimplerQMS represents a significant step toward modernisation, several SOPs such as SOP QA DOC11 confirm that digital adoption remains partial, with dual paper to electronic workflows continuing to strain staff and reduce process efficiency. More importantly, human resource shortages has been identified in the reports as high-risk with dependency on a small group of senior scientific and regulatory staff undermines the platform's ability to expand testing capacity or pursue new service lines an issue repeatedly noted across performance reviews and SANAS feedback.

These operational constraints limit the organisation's ability to fully leverage BMI initiatives, particularly those requiring responsiveness, scalability and digital maturity.

4.10.3.3 Revenue Logic and Financial Sustainability

The analysis identifies financial sustainability as the most structurally constrained component of the PCDDP's business model. Key issues include:

- Modest external income generation: Despite issuing twenty quotations in 2022, the Performance Review Portfolio shows that actual conversion into contract research income remains limited, suggesting either market hesitation or structural barriers to uptake.
- Dependence on ring, fenced public funding: The DSI remains the primary and most stable funder, with the platform lacking a diversified revenue base. This creates high exposure to government budget cycles and shifting policy priorities.
- High compliance, related cost structure: Maintaining GLP accreditation requires continuous investment in calibration, maintenance and quality assurance, costs that significantly exceed those of non, regulated research laboratories.
- Absence of a multi, year funding framework: Unlike OECD-linked infrastructures with predictable lifecycle funding, the PCDDP operates within short-term allocation cycles, making long-term planning and strategic investment extremely difficult.

BMI literature emphasises the need for financial flexibility and long-term capital stability for successful business model redesign. The findings demonstrate that the PCDDP's financial environment is rigid, risk-averse and externally controlled, limiting the unit's ability to pursue meaningful transformation.

Digital Transformation as a Business Model Enabler

Across several documents, including SOPs, SANAS inspection feedback and the DSI strategic presentations, digital transformation is positioned as essential to the PCDDP's future business model. Adoption of SimplerQMS as a tool for automated compliance, document control and audit readiness (codes: *digital capabilities*, *digital management*, *operational efficiency*) is one example and the building Management System (BMS) modernisation, enabling environmental data capture a core requirement for GLP accreditation. Also, emerging plans for dashboards, analytics and remote service delivery, which could support revenue diversification and improved client interfacing is another example. However, these initiatives remain constrained by slow implementation, limited digital maturity at institutional level and sporadic funding. As a result, digital transformation, while strategically prioritised, has not yet achieved the scale required to enable significant business model shifts.

4.10.3.5 Interpretation

The BMI perspective reveals an organisation with a clear understanding of its strategic imperatives such as diversification, digitalisation, efficiency enhancement, revenue stability and expanded stakeholder alignment. Yet the empirical evidence shows that transformative business model

redesign remains structurally inhibited. Incremental innovation is visible across service offerings, operational processes and digital systems, but deeper reform is constrained by external mechanisms including funding volatility, administrative centralisation, procurement inefficiencies and limited autonomy.

4.10.4 Integration of RBV, OI, and BMI: Explaining Sustainability Trajectories

An integrated application of the RBV, OI, and BMI provides a comprehensive explanation for the PCDDP's sustainability trajectory. Each framework illuminates a different dimension of the organisation's strategic environment; however, it is only when considered together that the causal mechanisms underlying sustainability outcomes become clear. The empirical findings demonstrate that the PCDDP's sustainability is not determined by organisational capability alone, nor solely by collaborative positioning or business model configuration, but by the relational interplay between these elements within a constrained national innovation system.

Interdependence Between RBV, OI, and BMI

RBV: What the PCDDP Possesses

RBV clarifies the internal capability base that underpins the organisation's strategic importance. Evidence from the SANAS GLP Inspection Reports (2021–2025), PCDDP Business Plan (2011) and Future Growth of PCDDP documentation confirms the presence of distinctive VRIN-aligned resources including GLP-compliant laboratories and AAALAC-aligned facilities, biosafety level 2/3 infrastructure unique in the national preclinical ecosystem, highly specialised regulatory and scientific expertise and more importantly long-standing accreditation credibility and a strong institutional reputation.

However, as demonstrated in Section 4.3, these capabilities are fragile without consistent investment, maintenance and retention strategies.

OI: How the PCDDP Extends its Capability Base

OI explains the mechanisms through which the PCDDP supplements and extends its internal capabilities. The empirical evidence shows extensive reliance on inbound and outbound knowledge flows such as methodological support from institutions such as CUT, Pharmacen and the Czech Centre for Phenogenomics, and international regulatory and scientific input from entities such as CEPI, Gate Foundation networks and Corteva. Outbound contributions in the form of GLP training, postgraduate supervision and diffusion of regulatory knowledge were also observed.

These collaborative linkages enable the PCDDP to bridge gaps in technical skill, regulatory insight and specialised scientific expertise.

BMI: How the PCDDP Adapts and Attempts to Reconfigure Itself

BMI report sheds light on organisational attempts to adjust value creation, delivery and capture the expansion of the service portfolio to include vaccine-related work, toxicity pipelines and advisory services. Furthermore, the gradual digitalisation through SimplerQMS and planned analytics dashboards is another example. Also, the emerging hybrid models combining regulatory, training and commercial services is another example showing PCDDP's attempts to adjust value creation, delivery and capture the expansion.

Yet BMI progress is incremental and heavily constrained by financial rigidity, procurement delays and limited decision-making autonomy.

Together, the three frameworks demonstrate that the PCDDP's sustainability depends upon the dynamic interaction between internal assets, collaborative networks and business model adaptability.

4.12 Systemic Constraints as Generative Mechanisms

Across all themes in Chapter 4, several constraints emerge as deeper systemic generative mechanisms that shape the PCDDP's sustainability outcomes. These mechanisms operate across multiple layers of the organisation's strategic environment and simultaneously affect RBV, OI and BMI dynamics.

4.12.1 Funding Volatility

As demonstrated in policy documents and SANAS feedback, irregular capital investments, short-term public funding cycles and the absence of a lifecycle renewal framework:

- undermine the maintenance of VRIN assets (RBV)
- destabilise long-term partnerships (OI)
- prevent strategic reinvestment essential for BMI

Thus, funding volatility is a structural mechanism that erodes capability reproduction and limits innovation.

4.12.2 Procurement and Administrative Rigidity

The repeated delays described in operational documents particularly in procuring consumables and replacing ageing equipment function as a systemic barrier to:

- operational agility and capability deployment (RBV)
- responsiveness to collaborative opportunities (OI)
- timely implementation of business model changes (BMI)

The impact is cumulative and compounds over time.

Fragmentation in the National System of Innovation

NSTF and STI Decadal Plan analyses show persistent misalignment between national priorities, institutional mandates and funding agencies. This undoubtedly weakens collaborative pathways (OI), increases strategic ambiguity (BMI) and reduces the organisation's ability to leverage its capabilities across the system (RBV). Fragmentation thus limits the PCDDP's ability to situate itself within coherent national research trajectories.

Digital Immaturity

The documents repeatedly highlight the limitations of digital infrastructure and digital integration within both NWU and the national research ecosystem. Digital immaturity without a doubt reduces the efficiency of capability utilisation (RBV), limits the PCDDP's absorptive capacity for external knowledge (OI) and more importantly undermines efforts to operationalise digital-driven business model innovation (BMI).

This systemic weakness affects all three theoretical domains simultaneously.

4.13 Emergent Sustainability Pathways

The combined framework reveals that sustainability is likely to be strongest when the following conditions are in place:

4.13.1 Systematic renewal of internal capabilities

This includes predictable funding for equipment replacement, structured human capital strategies and continuous accreditation maintenance.

Collaboration supported by conducive institutional and regulatory environments

Effective OI requires digital platforms for cross-institutional collaboration, streamlined procurement processes and alignment between national priorities and research infrastructure mandates

Business model innovation enabled by operational flexibility

BMI can only progress meaningfully when the organisation gains, greater autonomy over budget allocation and reinvestment, clearer governance structures and investment in digital systems that support efficiency and service diversification (Vong et al., 2025).

The empirical findings show that the PCDDP demonstrates partial alignment with these conditions but remains held back by system-level constraints not directly within its control.

The integrated RBV-OI-BMI lens shows that sustainability is not a single organisational achievement, but an emergent property shaped by the interaction of capabilities, networks and structural conditions. The PCDDP possesses strong scientific assets and demonstrates active

collaborative engagement and adaptive intent. However, the realisation of these strengths is inhibited by generative mechanisms such as funding instability, bureaucratic rigidity, labour market constraints and limited digital maturity.

The analysis therefore confirms that the sustainability of research infrastructures in developing contexts cannot be fully explained through organisational-level capabilities alone. Instead, sustainability is co-produced by the structural conditions of the wider innovation system. This integrated interpretation provides a foundation for the strategic recommendations that follow in Chapter 5 and establishes a coherent analytical bridge between the empirical findings and the dissertation's overarching conceptual framework.

4.14 Implications for the PCDDP and the Broader Research Infrastructure Landscape

The integrated interpretation of the empirical findings through the RBV-OI-BMI framework yields important implications for both the PCDDP and the national RI system. These implications extend beyond individual organisational practices and speak to the systemic reforms necessary for sustainable research capacity in South Africa. The analysis shows that sustainability emerges not from isolated organisational improvements but from the coordinated reinforcement of capability development, collaborative readiness, and business model adaptability within a supportive policy and funding environment.

Implications for the PCDDP

4.14.1 Strengthening VRIN Capabilities Through Structured Lifecycle Funding

The empirical findings confirm that the PCDDP's GLP-accredited infrastructure, high-containment laboratory facilities, and specialised human capital constitute rare and valuable capabilities. However, these assets are vulnerable to capability decay without predictable reinvestment. SANAS inspection reports and the 2025 Future Growth presentation highlight ageing equipment, the obsolescence of the previous Building Management System, and a capital renewal backlog exceeding R140 million.

To address this, the PCDDP therefore requires:

- A formal lifecycle funding proposal anchored in SARIR's long-term infrastructure planning principles.
- Alignment with NRF's evolving infrastructure funding models, including multi-year capital allocations and infrastructure maintenance grants.
- Evidence-based capital needs assessments, using GLP inspection findings, risk registers, and pricing-model data.

Strengthening VRIN resources is not merely a technical requirement but a strategic imperative for sustaining accreditation, scientific credibility, and national relevance.

4.14.2 Formalising Collaboration Governance

The analysis showed that collaborations with universities, international partners, regulatory bodies and industry actors compensate for internal capability gaps. However, these collaborations remain ad hoc and structurally vulnerable due to weak governance mechanisms. Formalisation should include:

- Structured engagement platforms with SAHPRA and DALRRD, addressing regulatory alignment, data requirements and scientific advisory mechanisms.
- Memoranda of Understanding (MoUs) with biotech firms and CROs, clarifying expectations, timelines and pricing frameworks.
- Consortium governance models, similar to the toxicology consortium referenced in earlier documents, providing shared infrastructure access and joint research opportunities.

These measures would substantially strengthen the PCDDP's absorptive capacity and network resilience, addressing constraints highlighted through the OI lens.

4.14.3 Accelerating Digitalisation as a Strategic Enabler

Digital capability appeared as one of the robust determinants of operational efficiency and long-term competitiveness. Yet the empirical evidence shows fragmented digital readiness, partial QMS integration, and insufficient data-system interoperability (Vong *et al.*, 2025).

Priorities thus without a doubt include:

- Complete integration and optimisation of SimplerQMS, including automated change-control tracking, document routing, and training management.
- Developing analytics dashboards to support performance monitoring, cost recovery, and client interactions.
- Strengthening interoperability between environmental monitoring, equipment scheduling, and financial systems.

These digital investments would support GLP compliance, improve turnaround times, and enable business model diversification toward remote inspections, virtual service models and digital client interfaces.

Repositioning the Business Model toward a Hybrid Logic

The PCDDP's current business model remains heavily dependent on public funding and constrained by administrative rigidity. Document analysis revealed growing interest from external clients but limited conversion due to procurement delays, pricing misalignment and insufficient market visibility. A hybrid model would undoubtedly entail integrating regulatory functions, commercial contract research, and innovation-oriented services into a unified offering, and developing tiered pricing structures that differentiate between academic partners, industry clients and government programmes. Moreover, strengthening service-level agreements to ensure predictable turnaround times and clear costings is also warranted.

Such repositioning is central to the BMI framework and would support the PCDDP's transition from grant dependency toward revenue diversification and financial resilience.

4.15 Implications for South Africa's National Research Infrastructure System

The sustainability challenges observed at the PCDDP are symptomatic of deeper systemic issues within South Africa's science, technology and innovation ecosystem. The findings point to the need for structural reforms that extend beyond the organisational level.

A National Lifecycle Investment Framework

Most challenges documented including ageing infrastructure, equipment failure risks and inconsistent renewal cycles reflect an absence of a coordinated national approach to research infrastructure financing. South Africa requires a national lifecycle funding model, aligned with SARIR and comparable to ESFRI/OECD best practices. Besides, predictable capital replacement cycles, reducing reliance on crisis-driven procurement and long-term infrastructure roadmaps, coordinated across departments to avoid duplication are essential for research infrastructure success. Such reforms would mitigate the chronic underinvestment documented in policy reports and reduce the structural vulnerability of high-end scientific facilities.

4.15.2 Better Alignment Across Regulatory, Research and Innovation Agencies

The fragmentation described in NSTF and DSI documentation undermines strategic coherence across the research ecosystem.

System-wide alignment should include coordinated regulatory-research planning, ensuring that GLP facilities are integrated into national health and pharmaceutical innovation strategies and joint advisory platforms across SAHPRA, DSI, NRF and DALRRD, reducing contradictory requirements and streamlining compliance processes. In addition, harmonised research infrastructure governance, promoting national interoperability and shared standards are also a requirement. Improved alignment would enhance collaboration efficiency and reduce the administrative burden limiting OI and BMI.

4.15.3 National Digital Research Infrastructure

The findings consistently underscore digital immaturity as a binding constraint. National actions should undoubtedly include:

- A coordinated digital research infrastructure programme, linked to the NRF's Digital Research Centre.
- Standards for validated data systems, enabling interoperability across research infrastructures.
- Investment in national e-research platforms, including data repositories, HPC access and digital compliance tools.

This would dramatically improve data integrity, collaboration efficiency and the scalability of research outputs.

4.15.4 Expanded Human Capital Pipelines

A recurring barrier relates to the scarcity of regulatory specialists, senior laboratory staff and GLP-trained technicians. More importantly, national reforms should prioritise:

- Dedicated training pipelines for regulatory science, laboratory animal science and GLP specialisations.
- Incentives for industry–academia mobility, strengthening absorptive capacity.
- Expanded postgraduate funding aligned with national research infrastructure needs.

Such interventions would reduce workforce vulnerability and enhance VRIN capability renewal across the system.

The integrated reading affirms that the sustainability of research infrastructures such as the PCDDP is fundamentally multidimensional. Internal organisational capability, networked knowledge flows, and business model adaptability are necessary but insufficient on their own. Sustainability emerges only when these are embedded within a supportive and coherent national system conducive to investment, digital maturity, regulatory alignment and strategic planning.

The implications therefore point toward a dual agenda comprising organisational strengthening within the PCDDP, and systemic transformation across South Africa's research infrastructure landscape.

This duality reflects the critical insight of the RBV-OI-BMI framework emphasizing that the organisational sustainability is co-produced by internal capabilities and external structures. The reforms identified through this integrated interpretation constitute the necessary conditions for South Africa to build and sustain internationally competitive research infrastructures capable of delivering long-term scientific, economic and societal value.

4.16 Chapter Summary

The integrated interpretation presented in this section demonstrates that the PCDDP's sustainability trajectory is shaped by a complex interplay of internal capabilities, external knowledge flows and adaptive business model mechanisms, each situated within the broader structural realities of South Africa's research ecosystem. While the organisation possesses distinctive VRIN-aligned assets and benefits from extensive collaborative networks, the analysis shows that these strengths cannot be fully leveraged without the systemic conditions necessary to support capability renewal, digital maturity and strategic autonomy. The combined RBV-OI-BMI lens illustrates that sustainability is not determined by any single domain but emerges as a composite outcome produced by the coherence, alignment and reinforcement of all three. The empirical evidence highlights both the strategic potential of the PCDDP and the binding constraints that restrict its progression toward a more resilient and innovation-oriented operating model.

Furthermore, interpreted through the Open Innovation lens, the findings indicate that the PCDDP's sustainability is intimately linked to the circulation of knowledge across organisational boundaries. Inbound flows provide critical expertise and technology access, while outbound flows support national capacity building and scientific visibility. However, systemic barriers ranging from digital maturity deficits to administrative constraints limit the organisation's absorptive capacity and reduce the extent to which collaborative potential can be fully realised. Collaboration therefore operates as both an enabler and a structural dependency, underscoring the need for coordinated support across the national innovation system to maximise its benefits.

The PCDDP is also actively pursuing BMI-aligned changes, however, the organisation operates within a system that restricts the realisation of more radical or sustainable business model transformation. These constraints reinforce the need to view BMI in conjunction with RBV and OI, recognising that business model adaptation is not solely an organisational decision but is shaped by the broader institutional environment.

CHAPTER 5: DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the overall discussion, conclusions, and recommendations arising from the study. The preceding chapters established a structured foundation for investigating how business-model innovation can strengthen the sustainability of research infrastructures in South Africa, using the PCDDP as an in-depth case study. Chapter 1 introduced the problem of persistent funding volatility, regulatory and administrative constraints, uneven digital maturity, and fragmented national coordination, all of which limit the long-term viability of South African research infrastructures. Chapter 2 advanced this problem by developing a conceptual framework integrating the Resource-Based View (RBV), Open Innovation (OI), and Business Model Innovation (BMI) to theorise how internal capabilities, external knowledge flows, and value-creation mechanisms collectively shape sustainability in non-commercial research infrastructures.

Chapter 3 outlined the qualitative, abductive research design used to examine these dynamics through systematic document analysis and comparative benchmarking. Chapter 4 applied the theoretical framework to the empirical case, generating five thematic areas that illuminate how capability strengths, structural pressures, collaborative arrangements, digital readiness, and business-model configurations interact within the PCDDP's operating environment. The chapter further demonstrated that although the PCDDP holds distinctive capabilities and engages in various innovation activities, its sustainability trajectory is moderated by deeper systemic constraints that lie beyond organisational control.

Against this background, the purpose of Chapter 5 is threefold. First, it synthesises the empirical findings in relation to the study's research questions, thereby demonstrating how the evidence responds to the original problem and research aim. Secondly, it interprets the findings through the RBV-OI-BMI framework to clarify the theoretical contributions of the study and show how the integrated model helps to explain sustainability dynamics in research infrastructures. Finally, the chapter provides practical implications, strategic recommendations, limitations, and directions for future research, offering a consolidated set of insights that can inform decision-making within the PCDDP, across South Africa's national research system, and within the broader scholarly literature.

Through this structure, the chapter positions the study's theoretical and empirical contributions within a coherent narrative, demonstrating how business-model innovation, when aligned with capability development, collaborative ecosystems, and digital transformation, can support more sustainable research infrastructures in resource-constrained contexts.

5.2 Synthesis of Findings in Relation to the Research Questions

This section synthesises the findings presented in Chapter 4 by responding directly to each of the study's five research questions. The discussion integrates empirical observations with the study's theoretical framework, clarifying how the PCDDP's sustainability trajectory is shaped by internal capabilities, collaborative arrangements, systemic constraints, digital maturity, and business-model adaptation.

RQ1: What are the key drivers of business-model innovation and sustainability within South African research infrastructures, particularly in the PCDDP?

The findings show that the strongest drivers of sustainability within the PCDDP arise from its internal scientific capabilities, regulatory credibility, and alignment with national science and technology priorities. GLP accreditation, AAALAC-aligned animal facilities, BSL-2/3 capabilities, and specialised analytical technologies position the platform as a rare national asset and enable participation in high-value preclinical studies. These capabilities are complemented by intangible drivers, including experienced scientific staff, institutional reputation, postgraduate training outputs, and longstanding collaborations with national and international partners such as Afrigen, CEPI, Pharmacen, and international universities.

The empirical analysis further highlighted strategic alignment with the STI Decadal Plan, SARIR, and national health-innovation agendas as an additional driver, creating a policy-supported rationale for sustained operations. Digital transformation initiatives, particularly the adoption of SimplerQMS and upgrades to environmental monitoring and BMS systems, also emerged as enabling forces that strengthen compliance, improve workflow efficiency, and support future business-model redesign. Collectively, these drivers confirm that the PCDDP's scientific depth, accreditation-driven credibility, and policy alignment form the foundation for sustainable business-model innovation.

RQ2: What barriers hinder the successful adoption and implementation of sustainable innovation strategies within the PCDDP?

The analysis revealed multiple interrelated barriers operating at both organisational and systemic levels. Funding volatility, including inconsistent capital investment and short grant cycles, remains the most significant impediment to long-term planning and equipment renewal. Operational inefficiencies, particularly procurement delays and limited autonomy over budgeting, undermine responsiveness to industry opportunities and delay implementation of new service offerings. Human-capital constraints including shortages of technical specialists, regulatory experts, and digital-competent staff further weaken capability renewal and limit absorptive capacity.

At system level, fragmentation within the National System of Innovation, inconsistent policy implementation, and weak integration between universities, regulators, funders, and industry restrict collaborative opportunities and hamper strategic alignment. Digital-maturity gaps, including incomplete integration of eQMS systems and limited interoperability across institutional platforms, also constrain the ability to modernise processes and comply with global data-integrity expectations. These barriers collectively weaken the translation of innovation drivers into sustained organisational performance (Lopes *et al.*, 2022; Nour & Arbussà, 2025:3262)

RQ3: How do digital capabilities influence financial sustainability and operational efficiency in research infrastructures?

Digital capabilities emerged as a pivotal enabler of both operational efficiency and financial resilience. The transition to SimplerQMS highlighted in multiple internal documents improves documentation accuracy, audit readiness, and turnaround time, reducing the administrative burden associated with GLP compliance. Enhanced environmental monitoring through the Building Management System upgrade supports quality control and reduces risks associated with equipment failure and environmental deviation.

Digital workflows enable better cost modelling, resource scheduling, and data integrity, all of which are central to improving pricing accuracy and controlling operational costs. However, the analysis showed that digital transformation remains incomplete. Interoperability challenges, under-resourcing of digital infrastructure, and limited staff readiness constrain the value that digital systems can deliver for PCDDP. Nevertheless, the findings indicate that digital capabilities when fully deployed serve as a core strategic asset that strengthens the PCDDP's competitive positioning, supports diversification into new services, and improves long-term sustainability.

RQ4: Which international best practices can be adapted to improve sustainability and innovation within the PCDDP?

Benchmarking against OECD, ESFRI, NSTF and leading international infrastructures revealed several transferable best practices. These include the use of lifecycle investment frameworks, which ensure predictable funding for equipment renewal, transparent access models combining public-value services with commercial offerings, and governance structures that integrate industry, academia, and regulatory bodies in shared decision-making. International infrastructures also emphasise digital-first operating models, FAIR data principles, and modular business architectures that support scalable service portfolios (Haak *et al.*, 2025).

The PCDDP is already aligned with several global standards such as OECD GLP and AAALAC, however, the empirical analysis shows that the platform could further strengthen sustainability by adopting structured pricing models, implementing advanced digital dashboards, and formalising

partnerships with regulators, industry and regional scientific networks. These practices would enhance the PCDDP's readiness to operate as a hybrid regulatory-commercial-innovation platform.

RQ5: What strategic recommendations can enhance the integration of business-model innovation and sustainability in South African research infrastructures?

The findings support a set of strategic recommendations centred on capability renewal, collaborative governance, digital modernisation, and adaptive business-model design. For the PCDDP, the analysis points to four priority areas:

1. Securing lifecycle funding through sustained engagement with SARIR, NRF and DSI to enable predictable capital renewal and reduce equipment-related vulnerabilities (Neema & Chandrashekar, 2021:134).
2. Strengthening collaboration governance, particularly with SAHPRA, DALRRD, and industry partners, to improve strategic alignment and expand opportunities for contract research (Bianchi *et al.*, 2021:1581).
3. Accelerating digital transformation, focusing on full integration of SimplerQMS, advanced analytics, and interoperable research-data systems (Vărzaru & Bocean, 2024).
4. Evolving and strengthen the hybrid business model, combining grant-funded regulatory services with commercial contract research, training as a service, and advisory offerings (Balconi & Lorenzi, 2017:480).

At national level, the analysis indicates a need for structural reforms, including unified governance mechanisms for research infrastructures, improved alignment across government departments, enhanced digital research platforms, and expanded talent pipelines.

5.3 Discussion of Findings Through the RBV-OI-BMI Lens

This study makes several substantive theoretical contributions to the fields of research infrastructure management, business model innovation, and organisational sustainability. The contributions arise from both the conceptual work undertaken in Chapter 2 and the empirical findings presented in Chapter 4, and together they advance understanding of how business model innovation can be applied within non-commercial scientific environments.

1. Extension of RBV, OI, and BMI Theory into Research Infrastructure Contexts

One of the study's central contributions is the extension of the RBV, OI, and BMI frameworks into the context of publicly funded research infrastructures. Existing literature predominantly applies these theories to commercial enterprises, technology firms, and entrepreneurial ecosystems, with limited attention given to non-commercial infrastructures that operate within regulatory, policy-driven, and resource-constrained environments (Azmat *et al.*, 2023; Singh and Ru, 2023).

This study demonstrates that research infrastructures possess distinctive resource bundles including advanced scientific instrumentation, accreditation status, technical expertise, and embedded routines that meet the VRIN criteria traditionally associated with competitive advantage in firms. The conceptual model developed in Chapter 2 shows how these capabilities can be understood as strategic assets within an RI context, thereby extending the RBV paradigm beyond its conventional commercial boundaries.

2. Conceptual Integration of RBV, OI, and BMI for Sustainable Research Infrastructures

A second major contribution lies in the integrated conceptual model that synthesises RBV, OI, and BMI into a unified framework explaining how sustainability is generated in research infrastructures. This integration demonstrates that:

- RBV clarifies the internal capability base,
- OI explains capability extension through collaborative networks, and
- BMI accounts for how organisations redesign value creation, delivery, and capture to ensure long-term viability.

The model provides a theoretically coherent explanation for sustainability as an emergent outcome of the interaction between capabilities, knowledge flows, and business-model structures. This synthesis offers a novel theoretical lens that can be applied to research infrastructures globally, particularly in developing-economy settings where sustainability challenges are acute.

3. Identification of Generative Mechanisms Limiting Business Model Innovation in Developing Systems

The study contributes new theoretical insight by demonstrating that research infrastructures in developing contexts face structural and systemic constraints that operate as generative mechanisms inhibiting the realisation of their internal capabilities. These include:

- funding volatility,
- fragmented governance,
- weak digital maturity,
- procedural rigidities (especially procurement), and
- national skills shortages.

The integration of these mechanisms into the RBV-OI-BMI framework advances critical realist theorisation of RIs by showing how deeper structural forces shape organisational sustainability, even when internal capabilities are strong. This adds an important contextual dimension to BMI scholarship, which often assumes organisational autonomy in business-model redesign (Wang *et al.*, 2025).

4. Empirical Validation of BMI in a Non-Commercial, High-Regulation Environment

The case of the PCDDP provides empirical evidence that BMI is viable and value-adding in research infrastructures, even though these organisations lack typical commercial incentives such as profit maximisation or market competition. The findings show that elements of BMI such as value-proposition diversification, digitalisation, governance adjustment, and hybrid revenue strategies are applicable and beneficial in high-regulation, grant-dependent environments. This expands BMI theory by demonstrating its relevance in mission-driven scientific infrastructures, thereby countering the implicit assumption in the literature that BMI applies primarily to commercial sectors.

5. Contribution to Sustainability Scholarship through the Lens of Scientific Infrastructure

The empirical analysis enriches sustainability scholarship by articulating how sustainability in research infrastructures is not simply a function of environmental or financial metrics, but rather a composite of scientific, operational, institutional, and policy dimensions. The framework shows that sustainability emerges when:

- scientific credibility and capability are preserved,
- operational robustness and efficiency are strengthened,
- external partnerships are leveraged to reduce capability gaps, and
- business-model components are adapted to changing conditions.

This broadens the concept of sustainability beyond traditional environmental or economic perspectives, demonstrating its multi-layered nature within scientific service environments.

6. Introduction of a Context-Specific Conceptual Framework for Developing Countries

Finally, the study offers a context-sensitive theoretical framework tailored to the realities of research infrastructures operating in developing economies. By explicitly incorporating the institutional weaknesses, administrative dependencies, and policy uncertainties characteristic of such environments, the study advances a theoretical model that is better suited to the Global South than existing RI frameworks built around OECD assumptions.

This contribution fills a recognised gap in the literature, responding to calls for theory development that accounts for the structural complexities of research ecosystems in developing countries.

5.4 Practical Implications

The findings generated through this study hold significant practical value for leaders of research infrastructures, institutional managers, and national policymakers responsible for shaping the governance and funding landscape of scientific facilities in South Africa. The implications derive

from the integrated RBV-OI-BMI framework and the empirical insights gained from the PCDDP case analysis. They offer actionable guidance for strengthening the sustainability, operational performance, and innovation capacity of research infrastructures in resource-constrained environments.

1. Strengthening Internal Capabilities through Structured Investment and Strategic Focus (RBV Implications)

The analysis underscores that valuable internal capabilities such as GLP accreditation, specialised instrumentation, regulatory expertise, and established quality-management routines form the strategic foundation of research infrastructures. However, these capabilities deteriorate without consistent renewal.

To address this, research infrastructure leaders should:

- Advocate for lifecycle investment mechanisms aligned with SARIR and NRF strategies, ensuring predictable funding for equipment replacement, digital upgrades, and facility renewal.
- Prioritise talent retention, succession planning, and institutional knowledge management to protect scarce regulatory and technical expertise.
- Embed digital capability development such as eQMS optimisation, data analytics, environmental monitoring systems) into core operational strategies rather than treating digitalisation as a supplementary project.

These measures ensure that internal VRIN capabilities remain viable and productive over time.

2. Enhancing Collaborative Mechanisms and Ecosystem Engagement (OI Implications)

The findings show that collaboration is both a strategic necessity and a structural dependency for research infrastructures.

Leaders should therefore:

- Formalise and deepen collaborative agreements with universities, regulatory agencies, industry partners, and global research networks.
- Strengthen governance arrangements for partnerships to ensure clarity of roles, continuity of engagement, and alignment with infrastructure mandates.
- Pursue joint research programmes, co-funded platforms, and shared infrastructure initiatives to expand expertise and reduce duplication within the national system.

These actions enhance absorptive capacity and enable infrastructures such as the PCDDP to supplement internal constraints with external knowledge and resources.

3. Reconfiguring Business Models for Hybrid Sustainability (BMI Implications)

The study demonstrates that research infrastructures cannot rely solely on grant funding or intermittent project income to achieve long-term sustainability. Business model innovation is therefore essential.

Leaders should:

- Redesign value propositions to include fee-for-service models, regulatory advisory functions, specialised training, and platform-based services.
- Strengthen pricing structures, performance management systems, and cost-recovery mechanisms to stabilise revenue flows.
- Integrate digital tools into business operations to improve transparency, project efficiency, and partnership coordination.

Such adaptations facilitate more resilient and diversified business models, better suited to the hybrid mandate of research infrastructures.

4. Implications for National Policymakers and Funding Agencies

The study highlights that many of the constraints limiting innovation and sustainability lie at system level rather than at organisational level. Policymakers should therefore:

- Develop a national lifecycle funding framework for research infrastructures to ensure predictable capital renewal and strategic investment.
- Strengthen cross-agency alignment between DSI, NRF, SAHPRA, industry bodies, and higher-education institutions to overcome fragmentation in the national innovation system.
- Establish national digital research infrastructure platforms enabling interoperability, secure data exchange, and digital audit trails across research infrastructures.
- Support human-capital pipelines in regulatory science, GLP compliance, laboratory management, and digital research capability.

These measures strengthen the institutional environment within which research infrastructures operate and allow BMI to be implemented effectively. Table 5 shows the implementation matrix.

Table 5: Practical Implications Matrix

Stakeholder	Key Strategic Action	Expected Outcome
Research infrastructure leaders	Diversify revenue through strengthened fee-for-service models, advisory services, and targeted industry partnerships.	Reduced volatility and enhanced financial resilience through broadened income streams (Satpathy <i>et al.</i> , 2025).
	Invest in digital capabilities such as QMS platforms, data analytics, and integrated monitoring systems.	Improved operational efficiency and stronger strategic asset base (Farida & Setiawan, 2022; Handoyo <i>et al.</i> , 2023; Najjar & Qandeel, 2025).
	Strengthen strategic partnerships with academia, government, industry, and global infrastructures.	Enhanced knowledge access, shared resources, and faster innovation (Meyer <i>et al.</i> , 2023; Mhlanga, 2024; Shonubi, 2025).
Policymakers and funding agencies	Implement incentives for hybrid funding models combining research grants with service-based income.	Greater financial stability and improved alignment between policy mandates and organisational performance (OECD, 2023; Purnamasari <i>et al.</i> , 2025).
	Support ecosystem-building initiatives such as innovation clusters and shared infrastructure programmes.	Increased open-innovation activity, reduced duplication, and amplified societal impact (Harrow <i>et al.</i> , 2021; Costa & Moreira, 2022).

5.5 Limitations and Future Research

Although this study provides meaningful insights into business model innovation and sustainability within South African research infrastructures, several limitations must be acknowledged to contextualise the findings and guide future research.

5.5.1 Limitations of the Study

The study is based on an in-depth analysis of the PCDDP as a single case. While this approach enabled a detailed understanding of organisational capabilities, collaborative networks, and business model dynamics, it limits the generalisability of findings across the broader research infrastructure landscape. Research infrastructures vary significantly in mandate, governance arrangements, scientific focus and funding architectures. As such, the insights derived from the PCDDP, although theoretically informative, may not fully capture the diversity of sustainability challenges experienced across other facilities.

The study relied exclusively on documentary sources for empirical analysis. This approach was appropriate given the richness of institutional, strategic, operational, and policy documentation available; however, the absence of primary interview data constrained the ability to triangulate internal perceptions, staff experiences, or tacit organisational processes not captured in formal documents. Some performance indicators, financial details, or organisational dynamics may therefore remain partially obscured. Although the available documents spanned more than a decade, gaps exist in the longitudinal record. Missing annual reports, incomplete financial performance data, and uneven documentation of specific operational periods limited the granularity of time-series analysis. Business model innovation is inherently dynamic, and certain transitions may not have been fully reflected in the available materials.

The analysis identified several structural mechanisms such as national funding cycles, regulatory frameworks, digital readiness, and skills pipelines that fall outside the organisational boundaries of the PCDDP. While these were interpreted through a critical realist lens as causal enablers or constraints, the study did not empirically interrogate these system-level determinants through engagements with policymakers, funders, or external partners.

Business model innovation, capability renewal, and sustainability trajectories evolve over time (Faccin *et al.*, 2025). Although the abductive analysis uncovered patterns and generative mechanisms, the study's cross-sectional orientation limits the ability to capture temporal shifts, path dependencies, and adaptive responses as they unfold.

5.5.2 Future Research Directions

To advance the understanding of sustainability and business model innovation in research infrastructures, future research should pursue several avenues.

Future studies should examine multiple research infrastructures across different scientific domains, institutional types, and national contexts to validate and refine the conceptual model developed in this study. Comparative case analysis would enrich understanding of how internal capabilities, collaborative ecosystems, and business model configurations vary across contexts.

More importantly, tracking business model innovation over time would allow researchers to examine how strategic adaptations unfold, how digital capabilities mature, and how funding, regulatory or collaborative pressures shape organisational trajectories. Integrating interviews, focus groups, or ethnographic observation with documentary analysis would provide deeper insights into tacit processes, organisational culture, and decision-making dynamics that documents alone may not reveal.

Given the centrality of external structures in shaping organisational sustainability, future research should explore interactions between research infrastructures, regulatory bodies, universities,

industry partners, and funding agencies. System-level studies could clarify how coordination mechanisms, policy frameworks, and national digital research infrastructures influence sustainability.

Research infrastructures in South Africa increasingly require hybrid revenue models. More focused studies on cost structures, pricing strategies, demand forecasting, and market development for scientific services would fill an important gap and support managerial decision-making. Given the study's findings on digital capability gaps, further research could examine digital readiness across South African research infrastructures and identify best practices for integrating eQMS systems, data analytics, automation, and digital compliance platforms.

Overall, these limitations do not detract from the significance of the findings, rather, they highlight valuable opportunities for future research to build on the theoretical, methodological, and practical contributions of this study. By extending this work through multi-case comparisons, longitudinal designs, ecosystem analyses, and deeper engagement with stakeholders, scholars can advance a more comprehensive understanding of how research infrastructures in developing economies achieve resilience, innovation, and long-term sustainability.

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Appendix A: List of Documents Analysed in the Study

This appendix provides a consolidated list of all institutional, policy, strategic, operational, and benchmarking documents included in the document analysis. The documents span internal PCDDP records, NWU institutional materials, national policy frameworks, strategic plans, and international benchmarking reports.

A.1 Internal PCDDP and NWU Documentation

DSI/NWU Preclinical Drug Development Platform – SANAS GLP Inspection, 27 November 2023

SANAS GLP Inspection Presentation (September 2021)
SANAS GLP Inspection Presentation (1 November 2022)
SANAS GLP Inspection Presentation (September 2025)
DST/NWU PCDDP Business Plan (2011)
PCDDP Presentation to Funder (Ms G. Loots, DSI): “Future Growth of PCDDP” (2025)
SOP QA DOC11 – Interim Management of SOPs During Transition to Electronic QMS
SimplerQMS Charter
NWU IT Presentation (Digital Transformation Briefing)
NWU Portfolio of Evidence System (KPA Tracking System)
2021 Performance Review Portfolio
2022 Performance Review Portfolio

A.2 National Reports, Policy Documents, and Strategic Plans

Department of Science and Innovation (DSI) Strategic Plan 2020–2025
Department of Science, Technology and Innovation (DSTI) Strategic Plan 2025–2030
Revised Strategic Plan 2020–2025 of the Department of Science and Innovation
STI Decadal Plan 2022–2032
Science, Technology and Innovation Indicators Report 2023
South African Research Infrastructure Roadmap (SARIR), 2016
SARIR/NICIS Briefing to the Portfolio Committee on Science and Technology (2021)
Higher Education, Science, Technology and Innovation Institutional Landscape Review Report (2020)
The Status of Innovation in the TVET Colleges (NACI Report)
National Science and Technology Forum (NSTF), AGM Minutes 2023
Current Challenges to Research and Innovation Systems in South Africa (NSTF, August 2024)

A.3 International Policy and Benchmarking Documents (OECD and Related Sources)

OECD (2019). Reference Framework for Assessing the Scientific and Socio-Economic Impact of Research Infrastructures
OECD (2020). Optimising the Operation and Use of National Research Infrastructures
OECD (2023). Very Large Research Infrastructures: Policy Report
Road mapping of Large Research Infrastructures (OECD Guidance Document)
University–Industry Collaboration: New Evidence and Policy Options (OECD, 2019)
Long-Term Sustainability of Research Infrastructures (OECD Policy Analysis)
Unlocking the Potential of Research Infrastructure Ecosystems to Tackle Societal Challenges (2025)

A.4 Benchmarking Reports, Academic Literature, and Expert Sources

CSIR–TUT Research Collaboration Report (2013–2016)

Building a Sustainable Research & HCD Ecosystem: Case Study of Two Wireless Communication Ecosystems (Mekuria *et al.*, 2013)

A.5 PCDDP Business Model Assessment Documents

BMI report - Evaluation of the Business Model of the DSI/NWU Preclinical Drug Development Platform (PCDDP) – Project Report (2024)

BMI report - Assessment and Improvement of the Business Model of the NWU Preclinical Drug Development Platform (PCDDP) – Project Report (2025)