

Toward a Compost Pharmacopoeia—A Conceptual Framework for Standardisation and Classification of Compost Quality

Kun Chen ¹, Naser Khan ¹, Mohammad Boshir Ahmed ^{1,2,3,*}, Peter Wadewitz ⁴, Philip Kwong ¹
and Volker Hessel ^{1,2,*}

¹ School of Chemical Engineering, Adelaide University, Adelaide 5005, Australia; kun.chen@adelaide.edu.au (K.C.); naser.khan@adelaide.edu.au (N.K.); philip.kwong@adelaide.edu.au (P.K.)
² ARC Centre of Excellence Plants for Space, Adelaide University, Adelaide 5064, Australia
³ Waite Research Institute, Adelaide University, Adelaide 5005, Australia
⁴ Peats Soil & Garden Supplies, Whites Valley, Adelaide 5172, Australia; peterw@peatsoil.com.au
* Correspondence: mohammadboshir.ahmed@adelaide.edu.au (M.B.A.); volker.hessel@adelaide.edu.au (V.H.)

Abstract

Compost quality assessment remains challenging due to substantial variation in standards, analytical methods, and reporting practices across jurisdictions and end-use applications. Differences in testing protocols and quality criteria limit data comparability among studies and compost products, while the absence of a common classification architecture hinders consistent interpretation of compost quality. This study proposes the Compost Pharmacopoeia Framework (CPF), a conceptual framework inspired by the organisational structure of pharmacopoeial systems. Existing standards, including AS 4454:2012, PAS 100:2018, and Regulation (EU) 2019/1009, were critically analysed to identify inconsistencies in physical, chemical, and biological quality assessment. Based on this analysis, the CPF integrates hierarchical classification, analytical methods, application-specific quality criteria, and reference materials within a unified framework for compost characterisation and reporting. The framework further introduces method equivalence concepts to facilitate comparison across non-equivalent analytical approaches. A representative experimental system is used to illustrate how compost quality information can be organised and interpreted within the proposed structure. In the representative nitrogen-regulated green-waste composting case, total nitrogen loss remained below 20%, while treatments were differentiated according to pH stability, nitrogen conservation, and germination performance, illustrating how CPF-organised data can support specific function interpretation. The CPF provides a foundation for improved data comparability, knowledge integration, and application-oriented compost classification, supporting more consistent communication among researchers, regulators, producers, and end-users.

Keywords: compost characterisation; data interoperability; method equivalence; compost classification; analytical protocols; performance-based evaluation; regulatory alignment



Academic Editor: Andrew S. Hursthouse

Received: 15 June 2026

Revised: 27 July 2026

Accepted: 1 August 2026

Published: 4 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Composting plays an important role in organic waste valorisation, circular bio-economy development, and soil regeneration [1]. As compost products are increasingly utilised in horticulture, agriculture, land rehabilitation, carbon management, and emerging bio-based industries, the assessment of compost quality has become progressively more important [2–4]. However, compost quality cannot be defined by a single set of criteria. The suitability of a compost product depends strongly on its intended application, with different

uses requiring distinct physical, chemical, and biological characteristics [5–8]. For example, materials suitable for land rehabilitation may not meet the requirements for seedling production or growing media, while composts rich in nutrients may require additional screening for salinity, ammonium toxicity, pathogen reduction, or contaminant risk before sensitive horticulture use [3,4,7,9]. Consequently, compost quality assessment requires frameworks that can accommodate diverse functions, feedstocks, processing histories and performance expectations.

A range of standards, regulations, and certification schemes has been developed internationally to support compost quality assurance, product safety, market confidence, and end-use sustainability. Examples include AS 4454 in Australia [10], PAS 100 in the United Kingdom [11], the Seal of Testing Assurance programme in the United States [12], and Regulation (EU) 2019/1009 within the European Union [13]. In addition, recent reviews and technical studies have further highlighted the importance of feedstock control, process design, maturity assessment, contaminant screening, and application-specific quality interpretation in compost production and use [14,15]. These frameworks have played an important role in promoting compost utilisation, defining minimum quality requirements, and supporting the safe use of compost products in different regulatory contexts.

In contrast, the pharmaceutical sector has long-established harmonised quality systems through pharmacopoeias such as the British Pharmacopoeia [16] and the European Pharmacopoeia. These systems provide a hierarchical structure consisting of general analytical methods, product-specific monographs, and certified reference materials, ensuring consistency, reproducibility, and regulatory reliability across laboratories and jurisdictions [16,17].

A comparable integrated system is currently lacking in compost science. Compost materials exhibit high biological and chemical variability, while analytical methods for key parameters—such as moisture content, pH, electrical conductivity, and stability—remain inconsistent across standards [18,19]. As a result, reported values can vary significantly depending on the selected method, leading to uncertainties in quality assessment and environmental performance evaluation [7,8,20,21].

One challenge in compost science is the absence of a common framework that links classification, analytical methods, and quality information within a single architecture. This contrasts with pharmacopoeial systems, where these components are organised in a structured and interoperable manner (Figure 1). In pharmaceutical science, classification, analytical methods, and quality specifications are organised within a unified pharmacopoeial architecture. In contrast, compost systems rely on multiple standards, methods, and reporting approaches that are often applied independently. This conceptual gap highlights the need for a structured framework that bridges these two dimensions.

The conceptual basis of linking compost classification and characterisation, environmental performance, and application context has been discussed in our previously published studies [22,23]. These studies examined environmental and ecosystem risks associated with advanced composting and evaluated pH-regulating and buffering strategies for improving nitrogen retention. Building on this research foundation, the present study formalises these elements within an integrated Compost Pharmacopoeia Framework for compost quality assessment.

Emerging composting technologies, including pH-regulating additives, process-responsive materials, sensor-based monitoring, and data-supported process control, are producing increasingly complex and time-dependent datasets. A structured framework is therefore needed not only to define analytical procedures but also to organise measurement context, method comparability, functional interpretation, and application-specific decision-making.

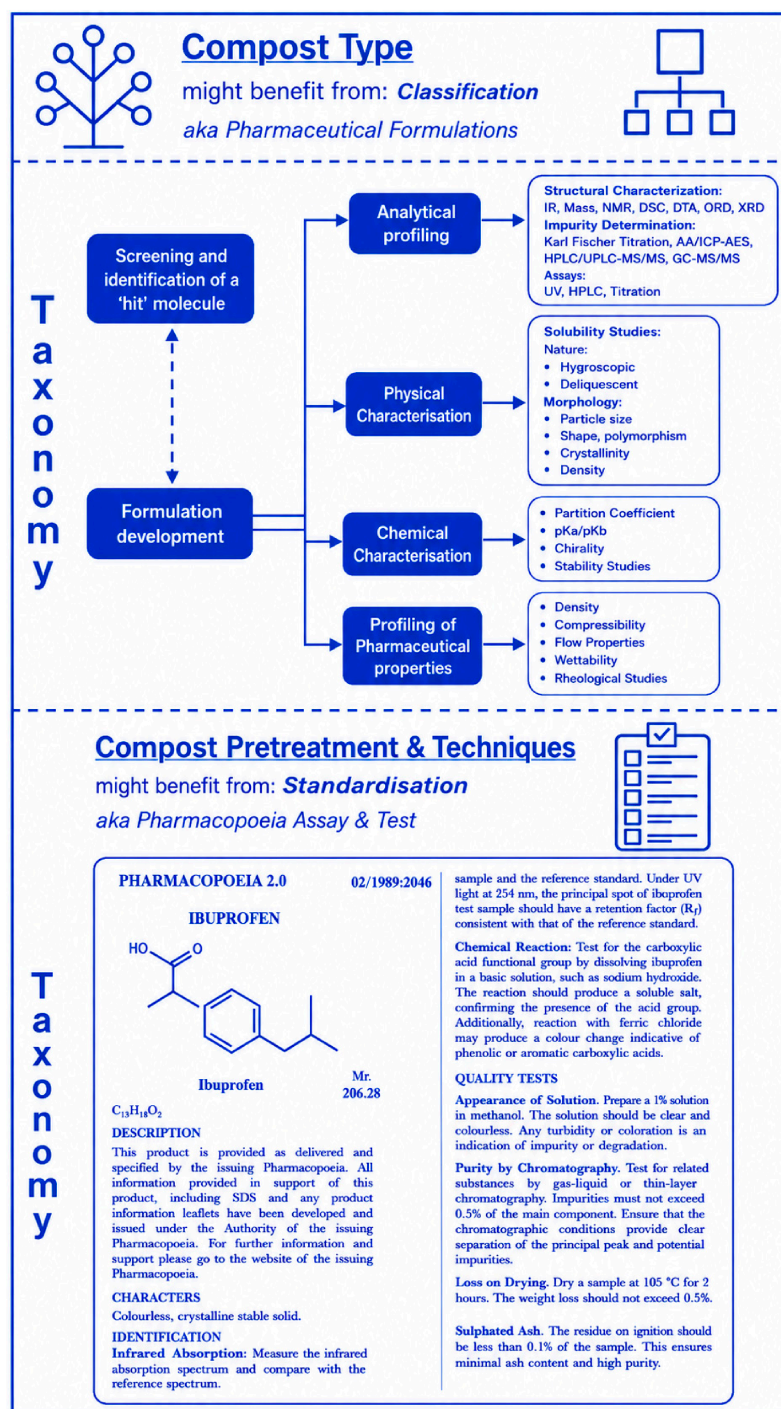


Figure 1. Conceptual gap between pharmaceutical systems and compost systems.

To address these limitations, this study proposes a Compost Pharmacopoeia Framework (CPF) as a structured framework for compost classification, characterisation, and quality information management. Drawing on pharmacopoeial principles, the CPF introduces a hierarchical framework that links three core components: (i) standardised analytical methods (general chapters), (ii) class-specific quality specifications (monographs), and (iii) certified reference materials for method validation (reference compost materials, RCMs). This approach aims to reduce methodological variability, improve inter-laboratory comparability, and enhance the reliability of compost quality assessment.

The pharmaceutical industry provides a strong precedent for the use of classification systems to standardise complex and variable materials. Frameworks such as the

Biopharmaceutical Classification System (BCS) demonstrate how categorisation based on key material properties can reduce empirical trial-and-error, support regulatory decision-making, and enable the definition of standardised testing and quality criteria [23–25]. Such systems also establish clear links between material characteristics, processing strategies, and performance outcomes, thereby improving reproducibility and comparability across studies and industrial applications [26].

In addition, classification-based approaches support regulatory processes through quality by design (QbD) principles, facilitating standardised quality assessment and, in some cases, enabling regulatory flexibility such as biowaivers [27–29]. Collectively, these advantages illustrate how structured classification systems can transform complex materials into predictable and standardised systems [30]. Inspired by these principles, a similar classification-driven approach may offer significant advantages for compost systems, where variability and lack of standardisation currently limit both scientific interpretation and practical implementation [31].

Despite the existence of multiple compost standards and extensive studies on compost maturity, stability, and nutrient dynamics, current approaches remain fragmented and lack an integrated framework for classification, testing, and reporting. Previous studies have primarily focused on individual parameters or specific applications, such as stability indices, nutrient content, or pathogen reduction, without establishing a unified system that links material properties to functional performance and regulatory requirements [5,7,32,33].

Furthermore, although international standards such as PAS 100 [34], AS 4454 [10], and EU Regulation 2019/1009 [13] provide baseline quality criteria, they differ substantially in methodology, parameter thresholds, and reporting formats, limiting cross-comparison and broader applicability [10,13]. This inconsistency has been widely recognised as a barrier to comparability and standardisation in compost research and application [20,35,36].

Importantly, no existing framework systematically organises compost materials in a manner analogous to pharmacopoeial systems, where classification, analytical methods, and reference materials are integrated into a coherent structure. This gap highlights the need for a conceptual yet operational framework that can unify compost classification and characterisation across scientific and regulatory contexts.

Because compost performance is inherently dependent on intended application, effective classification frameworks must account for both material characteristics and end-use requirements. Consequently, any classification system must be capable of accommodating diverse functional contexts while maintaining consistency in quality description and reporting.

Accordingly, the central hypothesis of this conceptual study is that organising compost quality information within a pharmacopoeia-inspired architecture can reduce interpretative variability and facilitate structured comparison across analytical methods. The objective of this work is to develop a conceptual yet operational framework that supports reproducibility in compost research, facilitates regulatory harmonisation, and provides a foundation for future standard development and validation.

2. Fragmentation of Compost Standards

2.1. Regional Standards and Regulatory Diversity

Compost quality is currently regulated through a range of national and regional standards, including PAS 100 in the United Kingdom, AS 4454 in Australia, and Regulation (EU) 2019/1009 within the European Union. While these frameworks aim to ensure product safety and minimum quality requirements, they differ significantly in scope, parameter definitions, and regulatory objectives [10,11,13,37].

PAS 100 primarily operates as a voluntary quality assurance scheme, focusing on process control, compost stability, and contamination limits. In contrast, AS 4454 de-

finest minimum requirements for composts, soil conditioners, and mulches, with specific thresholds for physicochemical properties, nutrient content, and biological safety [10]. EU Regulation 2019/1009 introduces a legally binding framework linked to fertilising product markets, categorising composts under Component Material Categories (CMCs) and integrating them into broader fertiliser regulations [13].

Despite these overlapping objectives, the three systems are not harmonised [38]. Differences in parameter limits, classification schemes, and compliance criteria lead to inconsistent definitions of “high-quality compost” across jurisdictions. Such inconsistencies hinder international trade and complicate regulatory alignment, while also limiting the comparability of research outcomes across different regions [39].

A representative overview of selected compost standards, regulations, certification programmes, and harmonisation initiatives across different regions is presented in Table 1. The comparison is not intended to provide an exhaustive legal or regulatory review but to illustrate the diversity of current approaches to compost quality assessment, including regulatory/product-level definitions, certification and quality assurance systems, and analytical standardisation frameworks. This comparison highlights that, despite the existence of multiple national, regional, and international systems, a unified framework integrating classification, analytical standardisation, validation, and structured reporting is still lacking. More specifically, PAS 100 and the US STA programme primarily operate as certification and quality assurance systems, whereas AS 4454 and EU Regulation 2019/1009 function as product and regulatory standards. In contrast, ISO frameworks mainly focus on analytical method standardisation rather than compost classification itself. In addition to national and regional systems, broader international harmonisation initiatives, including the European Compost Network (ECN) and international guidance frameworks, further demonstrate ongoing efforts toward improving interoperability and comparability in compost quality assessment [13,40,41]. Together, these systems illustrate the diversity of regulatory, certification, and analytical approaches currently applied across jurisdictions, while also highlighting the absence of an overarching framework integrating classification, validation, and standardised reporting.

Table 1. Representative comparison of selected compost standards, regulations, certification programmes, and harmonisation initiatives.

Aspect	UK (PAS 100)	Australia (AS 4454)	EU (2019/1009)	USA (STA)	Japan	ISO (Global)	International Harmonisation Initiatives
Type	Voluntary	National standard	Regulation	Voluntary	Regulation	International	International/Cross-jurisdiction
Main purpose	Quality assurance	Product standard	Market regulation	Product quality	Fertiliser control	Method standardisation	Harmonisation and interoperability
Classification	Limited	Basic categories	CMC system	Limited	Fertiliser-based	Not defined	Developing guidance frameworks
pH measurement	Defined (varies)	Defined	Not unified	Defined	Defined	ISO 10390 [18]	ISO-aligned
Stability test	AT4	GI	Not consistent	Respiration	Not standardised	Not defined	Under development/not unified
Organic matter	Varies	Defined (varies)	Varies	Defined	Defined	ISO-based	Method harmonisation
Reporting	Certification	Standard	Regulatory	Programme	Regulatory	Not applicable	Comparative guidance
Reference	[11]		[13]	[42]	[43]	[18,44]	[40,41]

2.2. Methodological Inconsistency in Compost Characterisation

Beyond regulatory differences, substantial inconsistencies exist in the analytical methods used to characterise compost properties. Key parameters such as moisture content, pH, electrical conductivity (EC), organic matter content, and biological stability can be determined using multiple standardised protocols (e.g., ISO, EN, or national methods), each producing different results depending on extraction ratios, incubation conditions, or analytical procedures [18,44].

For example, pH measurements are influenced by the solid-to-liquid ratio (e.g., 1:5 vs. 1:10), while compost stability may be evaluated using different indices such as AT4 or oxygen uptake rate (OUR), leading to non-equivalent results. Previous studies have demonstrated that these methodological differences can result in significant variability in reported values for the same compost material [20,39].

Moreover, equivalence between different analytical methods is rarely established. Unlike pharmaceutical systems, where analytical methods are rigorously validated and standardised, compost testing lacks a unified framework to ensure reproducibility and inter-laboratory consistency. As a result, datasets generated using different protocols are often not directly comparable.

2.3. Implications for Data Comparability and Application

The combined effects of regulatory fragmentation and methodological inconsistency have important implications for both research and industrial applications.

From a scientific perspective, inconsistent analytical approaches limit the ability to compare datasets across studies or to perform reliable meta-analyses. This is particularly problematic for life-cycle assessment (LCA) and environmental risk assessment (ERA), where standardised and comparable input data are essential for accurate evaluation [22]. Variability in reported compost properties introduces uncertainty into these models and reduces confidence in derived conclusions.

From an industrial perspective, the lack of harmonised standards complicates product certification and market access. Compost producers are required to comply with different regulatory frameworks depending on the target region, increasing operational complexity and compliance costs. In addition, the absence of standardised reporting formats reduces transparency and limits the scalability of compost-based products in international markets [39].

Overall, the current compost quality assessment landscape is characterised by fragmentation, methodological inconsistency, and limited interoperability. These limitations highlight the need for an integrated framework that links classification, analytical standardisation, and reference materials into a coherent and reproducible system.

3. Limitations of Current Methodologies in Compost Characterisation

3.1. Variability in Analytical Methods

A fundamental challenge in compost characterisation is the lack of standardised analytical methods across different testing protocols. Physical contaminant testing exemplifies this issue: fragment size limits differ significantly between countries, with Germany and the United Kingdom applying a 2 mm threshold, whereas the United States adopts a 4 mm limit [33]. Beyond physical thresholds, the definition of what constitutes a contaminant varies considerably. For example, paper is classified as a physical contaminant in UK methods but not in Germany, while U.S. methods provide no consistent classification guidance [33].

This methodological fragmentation extends to fundamental compost properties. Organic carbon determination illustrates the problem: the widely used Walkley–Black method

was originally developed for soil organic matter and is not specifically calibrated for compost matrices, and it cannot distinguish between organic and inorganic carbon (such as carbonates) [45]. Similarly, the carbon-to-nitrogen (C:N) ratio, although traditionally considered best practice, is neither practical nor reliable as a regulatory requirement, as accurate determination can be costly and does not consistently reflect compost maturity [46].

Stability assessment further demonstrates this variability. Indices such as AT4, oxygen uptake rate (OUR), and germination index represent different biological or physicochemical processes and are therefore not directly comparable [33]. Consequently, the same compost sample may yield substantially different stability values depending on the selected method.

This variability arises in part from the inherently heterogeneous nature of compost as a material. It is further compounded by the fact that different analytical methods target distinct physical, chemical, or biological processes. As a result, measured parameters are often method-dependent rather than intrinsic material properties, limiting their comparability across studies.

Importantly, these indices do not measure identical properties but rather reflect different biological or physicochemical dimensions of compost maturity and stability. Consequently, direct comparison between methods may lead to an inconsistent interpretation of compost quality and performance.

3.2. Lack of Method Equivalence and Validation

The absence of method equivalence and validation frameworks further constrains compost characterisation. Widely applied physical contaminant testing methods do not consistently use harmonised contaminant categories, size thresholds, or reporting criteria, leaving classification decisions partly dependent on individual laboratory procedures [33]. This lack of standardisation introduces significant inter-laboratory variability, particularly where laboratories apply different sample preparation, extraction, analytical, and reporting procedures [42,47].

Empirical evidence demonstrates the scale of this issue. For example, comparative studies in the United Kingdom have shown that different laboratories analysing identical compost samples containing known contaminants produced inconsistent results, particularly in identifying and quantifying paper fragments recovered from finished compost [33]. Such discrepancies highlight the absence of validated and reproducible analytical protocols, laboratory quality assurance, and inter-laboratory performance assessment [48].

A key limitation lies in the labour-intensive nature of current methodologies. Many compost analyses rely on manual sorting, extensive sample preparation, and time-consuming incubation procedures, making large sample sizes or repeated sampling impractical [35,47,49]. This restricts the development of statistically robust validation frameworks comparable to those established in pharmaceutical or environmental analytical systems.

The lack of certified reference materials further limits the ability to evaluate method accuracy and ensure inter-laboratory consistency [50,51]. Without standardised benchmarks, analytical outcomes remain dependent on laboratory-specific practices rather than reproducible system-defined criteria. These limitations indicate that current compost characterisation is not governed by an integrated analytical system but rather by a collection of independent and loosely connected methodologies, each developed for specific purposes without cross-method harmonisation.

3.3. Implications for Reproducibility

The issues outlined above are not isolated technical limitations but represent a systemic challenge in compost science. Variability in analytical methods, absence of validation frame-

works, and inconsistent inter-laboratory practices collectively undermine reproducibility and comparability.

As a consequence, it becomes difficult to establish consistent relationships between measured compost properties and functional outcomes, such as nutrient retention, greenhouse gas emissions, and plant growth performance. This limitation constrains the development of predictive models and evidence-based optimisation strategies for composting systems.

The implications extend to applied contexts, including life-cycle assessment (LCA) and environmental risk assessment (ERA), where inconsistent datasets introduce significant uncertainty and limit the reliability of comparative analyses [52]. Furthermore, existing compost quality assurance programmes typically evaluate only a limited subset of parameters relevant to high-value agricultural or horticultural applications, thereby restricting the comprehensiveness of material characterisation [5].

An integrated framework that systematically links analytical methods, classification systems, and certified reference materials is therefore essential. Such a framework would enable compost systems to transition from fragmented, method-dependent characterisation toward reproducible, comparable, and predictive scientific and industrial practices.

4. The Compost Pharmacopoeia Framework

To address the fragmentation and methodological limitations identified in previous sections, this study proposes a Compost Pharmacopoeia Framework (CPF) as an integrated system for compost classification, analytical standardisation, and quality assessment. The CPF adapts key principles from established pharmacopoeial systems, which provide structured approaches to analytical methods, product specifications, and reference standards [16,17].

The structure of the CPF is illustrated in Figure 2. The framework is organised as a hierarchical system consisting of three interconnected components: general chapters, monographs, and RCMs. These components collectively link analytical methods, classification systems, and validation procedures into a unified structure.

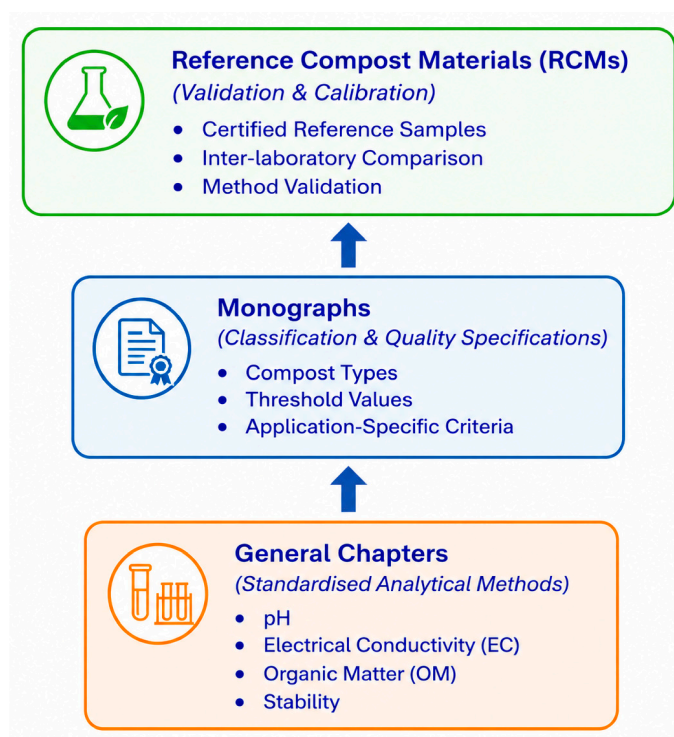


Figure 2. Structure of the Compost Pharmacopoeia Framework (CPF).

4.1. General Chapters: Sampling, Sample Preparation, and Standardised Analytical Methods

General chapters define the sampling, sample preparation, and standardised analytical procedures for determining key compost properties, including pH, electrical conductivity (EC), organic matter, and stability. For heterogeneous compost materials, analytical comparability depends not only on the measurement method but also on the generation of representative and comparably prepared test portions. The CPF, therefore, treats sample equivalence as a prerequisite for evaluating method equivalence. Existing international standards (e.g., ISO methods) may be used to define sampling strategy, composite sample generation, homogenisation, sample reduction, particle-size treatment, storage, preservation, and parameter-specific preparation requirements. These procedures are then integrated within a unified framework to improve consistency, traceability, and comparability across laboratories and studies [18,44,49,53,54].

Each general chapter should specify the applicable sampling protocol, composite sample design, homogenisation and reduction procedure, particle-size treatment, storage conditions, holding time, and preservation requirements. These procedures should be defined according to the compost matrix and analytical endpoint because sample preparation can influence physicochemical, nutrient, respiration, and microbiological measurements differently [49,54].

Following the establishment of sample equivalence, the CPF introduces the concept of method equivalence, through which different analytical approaches (e.g., AT4, oxygen uptake rate, and germination index) could be interpreted within a common reference context. This approach is intended to reduce discrepancies arising from methodological variability and to support reproducible compost characterisation.

In practical implementation, method equivalence would be assessed through paired measurements of the same reference compost materials using alternative analytical procedures. The resulting datasets could be evaluated using regression analysis for cross-calibration, statistical comparison between methods, agreement analysis, and uncertainty measurement assessment. Where appropriate, conversion functions or scale-transfer equations could then be developed to express results from one analytical method on the reference scale of another. However, equivalence should not be inferred from correlation alone; acceptable agreement limits, repeatability, reproducibility, uncertainty, and compost-matrix-specific bias would also need to be established. Where analytical methods measure related but non-identical biological processes, the objective would be interpretive comparability rather than direct numerical interchangeability.

4.2. Monographs: Classification and Quality Specifications

Monographs define classification criteria and quality specifications for different compost types based on feedstock origin, processing conditions, and intended applications. This approach is analogous to pharmacopoeial monographs, which establish standardised specifications for pharmaceutical substances [16].

Each monograph includes defined parameter ranges, threshold values, and application-specific criteria. By linking classification directly to analytical parameters, this component provides a structured basis for consistent quality assessment and facilitates alignment across different regulatory systems.

4.3. Reference Compost Materials (RCMs): Validation and Calibration

RCMs serve as standardised benchmark materials with well-characterised properties. These materials are used for method validation, calibration, and inter-laboratory comparison, addressing a critical gap in current compost analysis.

The concept of RCMs is aligned with the use of certified reference materials in analytical sciences, where they play a central role in ensuring measurement accuracy and comparability across laboratories [55]. Their implementation within the CPF enables systematic validation of analytical methods and supports the development of robust quality control systems.

4.4. Integration of Framework Components

The CPF integrates general chapters, monographs, and RCMs into a coherent system that links analytical methods, classification, and validation. General chapters provide standardised measurement protocols, monographs define classification and quality criteria, and RCMs ensure validation and reproducibility.

This integrated structure transforms compost quality assessment from fragmented and method-dependent practices into a more reproducible, comparable, and transparent system. By establishing clear relationships between measurement, classification, and validation, the CPF provides a foundation for harmonised compost standards and improved data interoperability across regions and applications.

5. Conceptual Application of the Compost Pharmacopoeia Framework

To demonstrate the practical applicability of the proposed Compost Pharmacopoeia Framework (CPF), a structured implementation pathway is presented by integrating generalised specifications derived from international standards (Table 2) with a representative experimental system.

Table 2. Generalised compost specification framework derived from international standards.

Category	Parameter	Typical Method(s)	Common Range/Requirement	Functional Role
Chemical	pH	ISO 10390 (1:10 extraction)	6.5–9.5	Controls NH ₃ volatilisation and microbial activity
	Electrical Conductivity (EC)	Aqueous extract	<4–6 mS cm ^{−1}	Indicates salinity and plant compatibility
	Organic Matter (OM)	Loss-on-ignition (LOI)	>30–50%	Reflects carbon content and stability
Biological	Stability	AT4/OUR/respiration index	Method-dependent and inconsistently defined (e.g., AT4 < 5–10 mg O ₂ g ^{−1} DM; OUR < 10–20 mg O ₂ kg ^{−1} OM h ^{−1} across standards)	Indicates maturity and biodegradation
	Germination Index (GI)	Seed germination test	>70–90%	Indicates phytotoxicity
Nutrient	Total Nitrogen (TN)	Kjeldahl method	Retention preferred	Determines fertiliser value and N efficiency

5.1. From Fragmented Standards to Generalised Specification

Existing compost standards include AS 4454, PAS 100, and the EU Fertilising Products Regulation [11,17]. Across these standards, common parameter categories—such as chemical (pH, EC, and organic matter), biological (stability and germination index), and nutrient-related indicators (total nitrogen)—can be identified across systems.

The generalised specification framework provides a unified template that abstracts these common elements, enabling compost characterisation to be interpreted within a consistent structure. This abstraction represents a critical step in transitioning from fragmented standards to a harmonised analytical and classification system.

5.2. Integration Within the CPF Structure

Within the CPF, the generalised framework is operationalised through three interconnected components (Figure 2). General chapters define standardised analytical methods for each parameter category, ensuring consistency in measurement, building upon internationally recognised protocols such as ISO 11465 [44] for moisture and ISO 10390 for pH determination [18,44]. Monographs translate the generalised parameter ranges into class-specific specifications based on feedstock type and application, while RCMs provide validation and calibration functions analogous to certified reference materials in analytical sciences [55].

This integration establishes a coherent system in which analytical methods, classification criteria, and validation processes are systematically linked, addressing the methodological fragmentation identified in Section 3.

5.3. Mapping Experimental Systems to CPF

To illustrate how experimental data can be incorporated into the CPF, a nitrogen-regulated in-vessel composting system is considered as an example. In this system, multiple treatment strategies—including natural acidity regulators and buffering agents—were evaluated under controlled conditions to assess pH stability, nitrogen retention, and compost maturity [22,23].

Using the generalised specification framework (Table 2), key experimental parameters can be directly mapped onto standardised categories. For example, observed pH values (8.1–9.1) fall within the generalised acceptable range, while reduced nitrogen loss (<20%) aligns with functional objectives related to nutrient retention. Similarly, improvements in stability and germination performance correspond to biological maturity indicators defined within the framework.

This mapping demonstrates that experimental results can be systematically interpreted within a unified specification system, rather than being evaluated in isolation.

5.4. Workflow Integration and Comparative Advantage

The CPF enables a structured workflow that integrates analysis, classification, and validation into a sequential and interconnected process. As illustrated in Figure 3, conventional approaches often rely on non-standardised methods, leading to inconsistent and non-comparable results, a limitation widely reported in compost characterisation studies [20].

In contrast, the CPF establishes a stepwise operational framework in which analytical procedures, classification decisions, and validation processes are systematically linked. This workflow ensures that data generated at each stage can be consistently interpreted and compared, reducing inter-laboratory variability and improving overall data coherence.

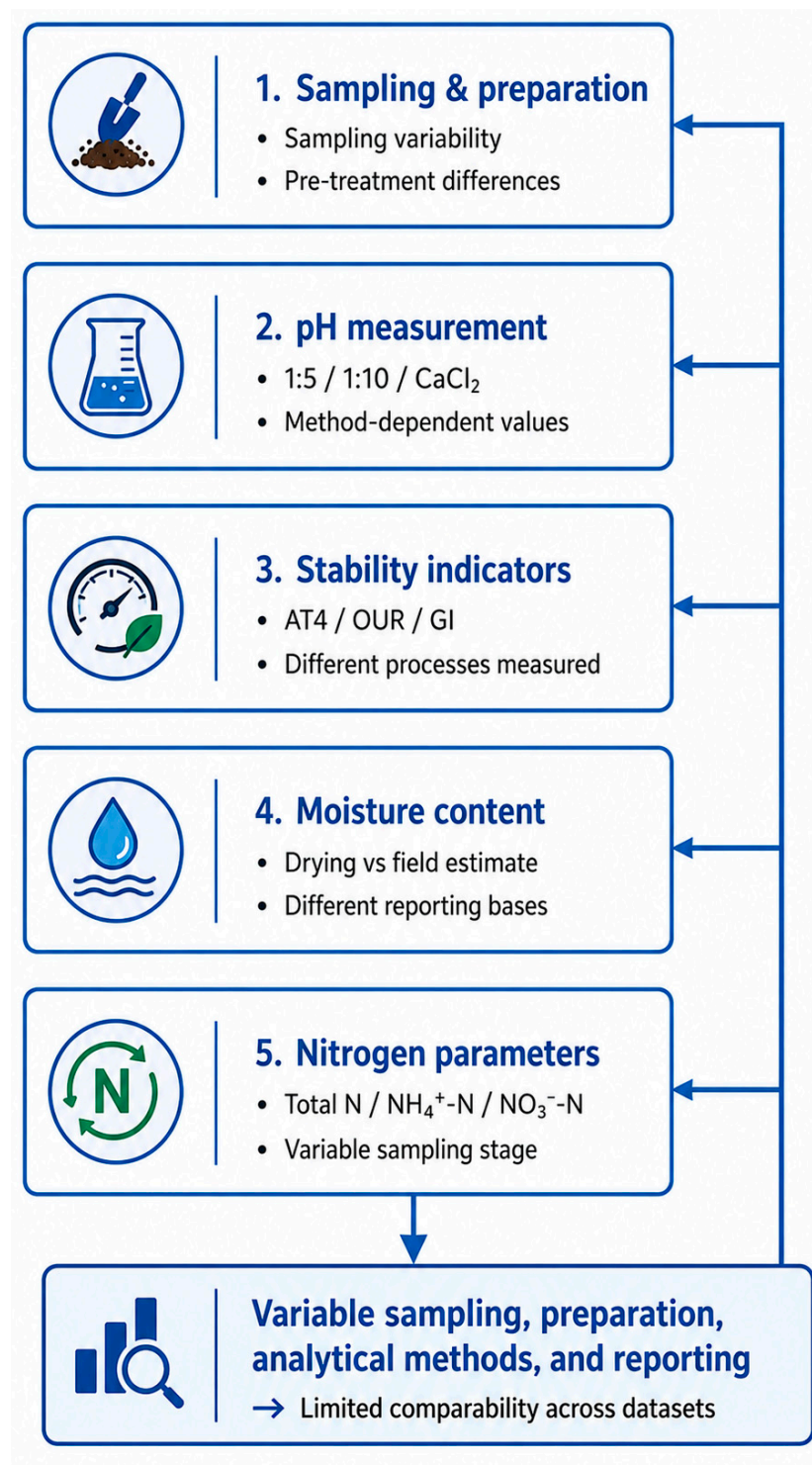
By embedding these components within a unified process, the CPF facilitates more reliable experimental design and supports the standardised reporting of compost systems across different studies and applications.

5.5. Implications for Research and Standardisation

The integration of generalised specifications with CPF components provides a practical pathway for advancing compost standardisation. For research, the framework enables consistent parameter interpretation and facilitates cross-study comparison. For industry

and regulatory systems, it offers a basis for harmonising quality criteria and reducing inconsistencies across standards.

Importantly, the CPF does not replace existing standards but provides a higher-level structure that aligns and integrates them. By bridging analytical methods, classification systems, and validation processes, the CPF supports the development of a more coherent and scalable compost quality assessment system.



(a)

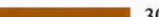
Figure 3. Cont.

COMPOST PHARMACOPOEIA 1.0

Green Waste Compost

CPF/2026/001

Green Waste Compost

Elemental Composition		Feedstock Composition	
C	48% 	Leaves	 50%
H	6% 	Branches	 30%
N	3% 	Residues	 20%
O	balance		

Compost Classification

Type: Green Waste Compost

Functional Class: Moderately alkaline, active N transformation system

Process Feature: pH-regulated nitrogen retention

Class: Functional Class II

Feedstock: Plant-derived green waste

Moisture: 50–60%

pH: Moderately alkaline

C/N ratio: 15–25

DESCRIPTION

This monograph applies to green-waste-derived compost systems used for the assessment of nitrogen retention under pH-regulated composting conditions. It is presented as an exemplary classified protocol within the Compost Pharmacopoeia Framework (CPF), demonstrating how compost materials and experiments may be described in a standardised format.

CHARACTERS

Brown to dark-brown heterogeneous particulate material with fibrous organic structure. The material should exhibit visible humification and maintain sufficient moisture for active biological transformation.

IDENTIFICATION

Feedstock Identity. The material shall be identified as compost derived predominantly from green waste of plant origin. Feedstock source and pre-treatment conditions shall be recorded.

Physicochemical Identity. Initial pH, moisture content, and C/N ratio shall be measured prior to incubation and used as baseline descriptors for protocol classification.

Functional Identity: The system shall be recognised as a compost matrix showing active nitrogen transformation and susceptibility to nitrogen loss under alkaline conditions.

DEFINED TESTING AND REPORTING REQUIREMENTS

pH. Report the measured value together with the solid-to-liquid ratio, extractant, equilibration time, measurement temperature, and sampling stage.

Moisture Content. Specify the drying temperature, drying duration, sample preparation procedure, and whether results are reported on a wet-mass or dry-mass basis.

Nitrogen Species. Report $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ together with the extractant, solid-to-liquid ratio, analytical technique, sampling stage, and dry-matter basis.

Total Nitrogen. Specify the digestion or instrumental method, sampling stage, calculation basis, and whether results are reported on a wet- or dry-mass basis.

PERFORMANCE INTERPRETATION

Interpret pH stability, nitrogen retention, nitrogen transformation, and germination performance in relation to the untreated control and the intended application.

A treatment may be classified differently depending on whether the main objective is pH stability, nitrogen conservation, maturity, or agronomic performance.

STRUCTURED REPORTING

The final report shall include material identity, classification basis, treatment conditions, analytical methods, sample preparation, units, reporting basis, sampling schedule, and time-series data for all monitored parameters. Any deviation from the defined procedure shall be declared.

STORAGE / HANDLING

Store compost samples in sealed containers under cool conditions prior to analysis. Avoid prolonged drying or contamination before testing.

(b)

Figure 3. (a) Variability and lack of standardisation in conventional compost assessment practices. Different studies and standards apply inconsistent methods, parameter definitions, and reporting formats, leading to limited comparability across datasets. (b) Example of a Compost Pharmacopoeia Framework (CPF) entry for green-waste compost, developed based on the experimental protocol reported in our previous study [23], illustrating standardised classification, defined testing procedures, and structured reporting.

To illustrate how the proposed Compost Pharmacopoeia Framework (CPF) may be implemented in practice, an exemplary classified protocol is presented below and further visualised in Figure 3a,b. Conventional compost characterisation (Figure 3a) is based on multiple analytical methods and parameter definitions that vary across standards and studies [10,20,35,42,56]. Key properties such as pH, stability, moisture, and nitrogen are measured using different protocols, resulting in inconsistencies and limited comparability. In contrast, the CPF-based framework (Figure 3b) introduces a structured system integrating standardised methods, classification, and validation to improve reproducibility and data comparability.

5.6. Example CPF Entry: Green-Waste Compost—pH-Regulated Nitrogen Retention System

Green-waste-derived compost is characterised by moderate alkalinity and a C/N ratio of 15–25, with moisture content typically maintained between 50 and 60%. Within the CPF, this system is classified as a functional compost type with active nitrogen transformation and a potential risk of ammonia volatilisation [22].

The experimental design consists of an untreated control and treatments incorporating pH-regulating additives. Key parameters, including pH, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and total nitrogen, are monitored over time using standardised analytical protocols defined in the general chapters.

Performance is evaluated based on pH stability, nitrogen retention relative to the control, and controlled nitrogen transformation. These criteria correspond to both chemical and functional indicators defined within the CPF monograph system.

Results are reported in a standardised and structured format, enabling comparability across compost systems and facilitating integration into broader classification and validation frameworks.

In conventional compost characterisation, analytical results are often reported as individual values, while important methodological details may be presented separately or omitted from the final dataset [20,45]. Under the CPF, these details form part of the analytical entry itself. A pH result would therefore be reported together with the solid-to-liquid ratio, extractant, equilibration time, measurement temperature, and sampling stage. Moisture content would specify drying temperature, drying duration, and wet- or dry-mass basis, while $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and total nitrogen results would identify the extraction or digestion procedure, analytical method, sampling stage, and reporting basis.

The practical advantage of this structure is that the measured value is interpreted together with its method and intended function. In the representative system, the observed pH range is therefore assessed alongside pH variability, nitrogen transformation, total nitrogen loss, and germination performance, rather than being compared with a single general threshold. This allows the same dataset to support different decisions depending on whether the main objective is pH stability, nitrogen conservation, or agronomic performance [22].

5.7. Potential Integration of Decision-Support Systems

An important future development direction for the Compost Pharmacopoeia Framework (CPF) is the incorporation of decision-support system (DSS) approaches as an operational layer linking analytical methods, classification systems, validation procedures, and application-oriented decision-making. DSSs have been widely applied in related sectors, including solid waste management, organic waste valorisation, agricultural nutrient management, and environmental risk assessment, where heterogeneous analytical, regulatory, and performance-based information must be translated into practical management strategies [57–60]. Within the CPF, a DSS would not replace the framework itself but

would provide a structured decision layer that converts standardised analytical outputs into interpretation, classification, risk screening, and application recommendations.

Conceptually, a CPF-linked DSS could support several sequential functions. First, feedstocks could be screened and classified according to source, contamination risk, and suitability for composting [14,57,61]. Second, standardised analytical data generated through CPF general chapters, including pH, electrical conductivity, moisture, organic matter, nitrogen forms, maturity indices, and contaminant indicators, could be interpreted against class-specific monograph criteria [58,59]. Third, risk-based screening could identify materials requiring restriction, further maturation, contaminant testing, or non-agricultural use [60]. Finally, compost products could be classified according to intended application, such as fertiliser-supporting compost, liming material, soil conditioner, carbon amendment, or restricted-use material. Particular attention should be given to feedstocks with elevated contamination potential, such as sewage sludge, industrial organic residues, and other mixed or poorly traceable organic waste streams. Within a CPF-linked DSS, these materials could be assigned to risk-based categories according to heavy metal content, pathogen indicators, persistent organic contaminants, emerging pollutants, and source traceability. Such classification would allow high-risk materials to be restricted from agricultural use, redirected to non-food or non-agricultural applications, or subjected to additional treatment and verification before inclusion in compost products [61–65].

To illustrate how such a DSS layer may operate, a simplified decision-support matrix is presented in Table 3, using the nitrogen-regulated green-waste composting system reported in our previous study as a representative case [22]. This example is not intended to define universal thresholds or represent a fully validated DSS model. Rather, it demonstrates how CPF-derived analytical outputs can be translated into structured interpretation and decision pathways. In that study, green-waste-derived compost was treated with natural acidity regulators and agri-buffering adjuvants under controlled in-vessel composting conditions. Key indicators included moisture stability, pH regulation, nitrogen retention, carbon–nitrogen evolution, germination performance, and integrated multi-criteria treatment ranking.

Table 3. Illustrative CPF-DSS decision-support matrix based on a nitrogen-regulated green-waste composting case study.

DSS Module	CPF Input/Indicator	Example Finding from Case Study	DSS Interpretation	Possible Decision Output
Process condition screening	Moisture condition	Initial moisture was approximately 50% and was maintained within a composting-supportive range	Process conditions were suitable for microbial activity and aerobic composting	Acceptable process condition
pH regulation assessment	pH range and variability	Buffered systems stabilised pH within 8.1–9.1; G6 showed the lowest pH variability, SD = 0.22	Strong buffering performance and reduced ammonia volatilisation risk	Prefer G6 where pH stability is the primary objective
Nitrogen conservation	Total nitrogen loss	Total nitrogen loss remained below 20% across treatments	Nitrogen was largely retained within the composting system	Acceptable nitrogen-retention performance

Table 3. *Cont.*

DSS Module	CPF Input/Indicator	Example Finding from Case Study	DSS Interpretation	Possible Decision Output
Biological maturity and phytotoxicity	Germination rate and seedling vigour index	G3 showed the highest SVI = 1300; G2 showed SVI = 1250; G5 showed reduced germination rate of 75%	G3 and G2 showed the most favourable germination-related performance under the conditions of the representative case study	Prioritise G2/G3 for further agronomic evaluation; restrict or optimise G5 pending additional assessment
Carbon–nitrogen balance	C/N evolution	C/N decreased from approximately 17 to 10–12; G6 showed strong later-stage C/N improvement	Indicates compost maturation and organic matter stabilisation	Prefer G6 where C/N stabilisation is prioritised
Integrated treatment ranking	Multi-criteria weighted score	G2 achieved the highest total score = 9; G6 ranked second with score = 7	G2 provided the best balance across process, nitrogen, and maturity indicators	G2 ranked highest under the selected multi-criteria weighting system; G6 ranked second
Risk-based application screening	Germination inhibition and poor integrated score	G5 had the lowest integrated score = −3 and reduced germination	Potential operational or agronomic limitation	Require further optimisation before application
Contaminated feedstock screening	Feedstock source, heavy metals, pathogen indicators, persistent contaminants, emerging pollutants	Sewage sludge or poorly traceable organic residues may present elevated contamination risks	High-risk materials require stricter classification and verification before agricultural use	Restrict agricultural application, require further testing, or redirect to non-agricultural use

Treatment definitions: G1, untreated control; G2, wood vinegar treatment at 10% *v/w*; G3, FeSO₄·6H₂O treatment at 0.4 mol kg^{−1}; G4, citric acid monohydrate treatment at 0.16 mol kg^{−1}; G5, sodium acetate/acetic acid buffer treatment at 0.70 mol kg^{−1}; and G6, K₂HPO₄/KH₂PO₄ phosphate buffer treatment at 0.40 mol kg^{−1}. Treatment codes and dosages were derived from the representative experimental study cited in the table.

This illustrative matrix demonstrates how a CPF-linked DSS could accommodate both individual analytical indicators and integrated multi-criteria assessment outputs. For example, a treatment may be classified differently depending on the decision objective: G6 may be preferred for pH stabilisation and C/N improvement, whereas G2 may be recommended as the best overall treatment when multiple process and maturity indicators are considered together. This distinction is important because compost quality is rarely determined by a single parameter; rather, it depends on the intended use, regulatory context, agronomic function, and environmental risk profile.

Therefore, DSS integration could provide a pathway for translating the CPF from a conceptual standardisation framework into a more operational assessment tool. Future development would require formal weighting procedures, validation using reference compost materials, calibration across different feedstocks, and alignment with regional regulatory systems and application-specific requirements. Nevertheless, the example demonstrates that CPF-derived data can be organised into decision-relevant categories, supporting more transparent, reproducible, and application-specific compost quality assessment.

6. Discussion

The findings of this study reveal that the current limitations in compost science are not merely methodological inconsistencies but reflect a deeper structural issue: the absence of a unified framework that integrates analytical methods, classification systems, and validation procedures. Although existing standards such as AS 4454, PAS 100, and EU Regulation 2019/1009 provide essential guidance, their fragmented implementation results in inconsistencies in data generation and interpretation across regions. This fragmentation has been widely recognised as a barrier to comparability and standardisation in compost research [20,39].

A critical consequence of this fragmentation is that many reported compost properties are method-dependent rather than intrinsic material characteristics. For instance, parameters such as pH, stability, and organic matter content can vary significantly depending on extraction ratios, incubation conditions, or analytical techniques [10,45]. Similarly, stability indices such as AT4, oxygen uptake rate (OUR), and germination index reflect different biological or physicochemical processes and are therefore not directly comparable [5,32]. As a result, datasets generated under different protocols may not be directly interpretable, limiting both reproducibility and the development of predictive relationships between compost properties and functional outcomes.

By embedding these components within a unified process, the CPF facilitates more reliable experimental design and supports the standardised reporting of compost systems across different studies and applications. This integration is conceptually aligned with established analytical systems in pharmaceutical sciences, where coordinated use of standardised methods and reference materials underpins reproducibility and regulatory reliability [16,66,67].

Importantly, the CPF extends beyond conventional threshold-based evaluation by enabling performance-oriented interpretation and facilitating method equivalence across different analytical contexts. As such, it provides a foundation for improved comparability, enhanced regulatory confidence, and more consistent translation of experimental findings into practical applications [35].

Another significant contribution of the CPF lies in its potential to support functional and application-oriented classification. Future extensions of the CPF may further incorporate broader categories of quality indicators beyond conventional physicochemical parameters. These may include biological functionality, microbiological quality, contaminant risk assessment, agronomic performance, nutrient-release behaviour, carbon sequestration potential, and environmental impact indicators. In future implementations of the framework, incorporation of such attributes could support more application-oriented compost classification and improve the ability of the framework to evaluate compost suitability across different agricultural, environmental, and industrial contexts. This extension would further support the transition from threshold-based compost evaluation toward performance-oriented and application-specific assessment systems. Current standards primarily rely on threshold-based criteria, which often lack direct linkage to performance outcomes such as nutrient retention, greenhouse gas emissions, or plant growth response [5,52]. By contrast, the CPF links classification with analytical parameters and functional objectives, enabling compost materials to be evaluated based on both quality compliance and application relevance. This approach aligns with emerging trends in environmental and agricultural systems, where performance-based evaluation is increasingly emphasised.

The conceptual application presented in Section 5 demonstrates that CPF can effectively bridge experimental research and standardisation. By mapping experimental data—such as pH regulation and nitrogen retention—onto a generalised specification framework, the CPF enables consistent interpretation across studies. This is particularly important

for emerging technologies, including pH-responsive materials and nitrogen conservation strategies, where methodological inconsistency currently limits comparability [22].

From a regulatory perspective, the CPF offers a pathway toward harmonisation without replacement. Existing standards are embedded within regional regulatory systems and cannot be easily unified. However, the CPF operates as a higher-level framework that aligns these systems through shared analytical principles and classification structures. Similar approaches have been successfully implemented in other domains, such as pharmaceutical quality systems and environmental monitoring frameworks, where overarching structures enable interoperability across regulatory boundaries [28]. However, regulatory harmonisation alone does not automatically ensure comparability across research platforms. Scientific studies are not always conducted within formal regulatory compliance frameworks, and differences in sample collection, sample preparation, extraction procedures, operator interpretation, instrument calibration, and laboratory-specific practices can still introduce variability even when similar or nominally identical methods are applied. In addition, differences between national regulatory systems may reflect local feedstock availability, environmental priorities, agricultural practices, economic conditions, technological capacity, and enforcement structures, rather than methodological inconsistency alone. Therefore, the CPF should be interpreted not only as a regulatory harmonisation tool but also as a broader structure for improving transparency in method selection, reporting, validation, and inter-laboratory comparison.

Despite its advantages, the CPF remains a conceptual framework and requires further development for practical implementation. Several key challenges must be addressed. First, the establishment of method equivalence relationships requires systematic comparison and validation across analytical methods, which remain limited in compost research [20]. Second, the development of RCMs will require coordinated efforts in material production, characterisation, certification, and inter-laboratory testing, consistent with established requirements and guidance for reference materials [19,51,55].

A particular challenge is the temporal instability of biologically active compost. Compost is a heterogeneous organic matrix that may continue to undergo mineralisation, moisture exchange, gas release, microbial succession, and changes in extractable nutrient pools during storage [35,45]. Consequently, a single bulk compost material cannot be assumed to retain all physicochemical and biological properties indefinitely. The suitability and period of validity of an RCM would therefore need to be defined separately for each certified property.

Candidate RCMs would require property-specific characterisation, homogeneity assessment, short- and long-term stability studies, uncertainty evaluation, specified storage conditions, and defined periods of validity [50,51]. Different forms of reference materials may therefore be required for different analytical purposes. For physicochemical measurements, homogenised, dried, milled, sieved, and sealed materials may provide relatively stable matrix reference materials for elemental composition, organic matter, contaminants, and selected extraction-based properties. For biological or respiration-based measurements, freshly prepared materials, short-term proficiency-testing samples, or reference datasets with defined stability windows may be more appropriate. Each RCM would require homogeneity assessment, stability testing, specified storage and handling conditions, an expiry period, and periodic recertification, consistent with established principles for proficiency testing and inter-laboratory comparison [51,55].

From a practical and commercial perspective, initial RCM development could focus on a limited number of mature and widely used compost matrices, such as mature green-waste compost, with certification restricted to properties demonstrated to remain stable. The CPF may therefore distinguish among certified physicochemical RCMs, time-limited

biological reference materials, and proficiency-testing materials, rather than relying on a single universal form of reference compost. Third, the formulation of monographs for diverse compost types must account for variability in feedstocks and applications, requiring a balance between flexibility and standardisation.

In addition, adoption of the CPF will depend on engagement from both research and industry stakeholders. For researchers, the framework provides a structured basis for experimental design and data reporting. For industry and regulators, it offers a tool to improve quality assurance, certification, and market interoperability. However, implementation is likely to occur progressively, beginning with the harmonisation of key analytical methods and gradually expanding toward full framework integration.

Overall, the CPF represents a transition from fragmented, parameter-based approaches toward a systems-oriented model of compost standardisation. By explicitly linking analytical methods, classification systems, and validation tools, the framework provides a foundation for improving reproducibility, comparability, and functional interpretation in compost science. While further validation and development are required, the CPF establishes a clear conceptual pathway toward a more coherent and scalable compost quality assessment system.

7. Conclusions

This study proposes the Compost Pharmacopoeia Framework (CPF) as a novel and structured approach to compost classification and quality assessment. By integrating analytical methods, classification systems, and validation procedures into a coherent framework architecture, the CPF addresses key limitations in current compost characterisation.

Through the development of a generalised specification framework and its application to a representative experimental system, this study demonstrates how compost data can be systematically interpreted within a consistent structural context.

Importantly, the CPF introduces a method equivalence mechanism that enables the interpretation and comparison of results generated from non-equivalent analytical protocols (e.g., AT4 and OUR), addressing the method-dependent nature of current compost characterisation. By providing a structural bridge between these heterogeneous measurement systems, the CPF facilitates more consistent data interpretation and supports cross-study comparability without requiring strict methodological uniformity.

Overall, the CPF represents a significant step toward the development of a standardised and scalable compost quality assessment system. Future work should focus on refining the framework, developing detailed monographs, and establishing reference materials to enable its practical implementation.

Author Contributions: K.C.: Conceptualisation, Methodology, Investigation, Formal Analysis, Visualisation, Writing—Original Draft Preparation, Writing—Review and Editing. N.K.: Resources, Writing—Review and Editing. P.W.: Resources. M.B.A.: Supervision, Investigation, Formal Analysis, Writing—Review and Editing. P.K.: Supervision, Writing—Review and Editing. V.H.: Conceptualisation, Methodology, Investigation, Formal Analysis, Supervision, Project Administration, Funding Acquisition, Writing—Original Draft Preparation, Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This project was undertaken through the Industry Doctoral Training Centre (IDTC) scholarship, funded by the University of Adelaide and the Government of South Australia, under grant number 29072022. Support from the Australian Research Council (ARC) Centre of Excellence “Plants for Space” (P4S) (grant number CE230100015) is also appreciated.

Data Availability Statement: No new data were created or analysed in this study.

Acknowledgments: We acknowledge the support provided by Peats Soil & Garden Supplies. The content of this publication is the sole responsibility of the authors and does not necessarily reflect the views of the Government of South Australia or any affiliated organisations.

Conflicts of Interest: Peter Wadewitz was employed by the Peats Soil & Garden Supplies, Adelaide, Australia. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Otoo, M.; Drechsel, P. *Resource Recovery from Waste*; Taylor & Francis Group: New York, NY, USA, 2018.
- Rashwan, M.A.; Naser Alkoaik, F.; Abdel-Razzak Saleh, H.; Blaqueza Fulleros, R.; Nagy Ibrahim, M. Maturity and stability assessment of composted tomato residues and chicken manure using a rotary drum bioreactor. *J. Air Waste Manag. Assoc.* **2021**, *71*, 529–539. [\[CrossRef\]](#) [\[PubMed\]](#)
- U.S. Environmental Protection Agency. *Environmental Value of Applying Compost*; United States Environmental Protection Agency: Washington, DC, USA, 2025.
- Bernal, M.P. An overview of conventional and emerging aspects of compost: Quality indicators for agricultural uses, emerging contaminants and technological innovations. *Front. Sustain. Food Syst.* **2026**, *10*, 1785912. [\[CrossRef\]](#)
- Bernal, M.P.; Alburquerque, J.A.; Moral, R. Composting of animal manures and chemical criteria for compost maturity assessment: A review. *Bioresour. Technol.* **2009**, *100*, 5444–5453. [\[CrossRef\]](#) [\[PubMed\]](#)
- Gómez, R.B.; Lima, F.V.; Ferrer, A.S. The use of respiration indices in the composting process: A review. *Waste Manag. Res.* **2006**, *24*, 37–47. [\[CrossRef\]](#) [\[PubMed\]](#)
- Kong, Y.; Zhang, J.; Yang, Y.; Liu, Y.; Zhang, L.; Wang, G.; Liu, G.; Dang, R.; Li, G.; Yuan, J. Determining the extraction conditions and phytotoxicity threshold for compost maturity evaluation using the seed germination index method. *Waste Manag.* **2023**, *171*, 502–511. [\[CrossRef\]](#) [\[PubMed\]](#)
- Tsabedze, S.A.; Otieno, B.; Thomas, A.R.; Getahun, S.T. Phytotoxicity and quality in compost: A concise review of Sewage Sludge and Green Waste applications. *J. Mater. Cycles Waste Manag.* **2025**, *27*, 4041–4058. [\[CrossRef\]](#)
- Brinton, W.F. *Compost Quality Standards and Guidelines: An International View*; Woods End Research Laboratory Inc.: Mount Vernon, ME, USA, 2000; Volume 10, p. 42.
- AS 4454-2012; Composts, Soil Conditioners and Mulches (Including Amendment 1). Standards Australia: Sydney, NSW, Australia, 2012.
- PAS 100:2018; Specification for Composted Materials. British Standards Institution: London, UK, 2018.
- US Composting Council. *Seal of Testing Assurance Program*; US Composting Council: Raleigh, NC, USA, 2024.
- European Parliament and Council of the European Union. *Regulation (EU) 2019/1009 of the European Parliament and of the Council Laying Down Rules on the Making Available on the Market of EU Fertilising Products*; European Parliament and Council of the European Union: Brussels, Belgium, 2019.
- Manea, E.E.; Bumbac, C.; Dinu, L.R.; Bumbac, M.; Nicolescu, C.M. Composting as a sustainable solution for organic solid waste management: Current practices and potential improvements. *Sustainability* **2024**, *16*, 6329. [\[CrossRef\]](#)
- Noor, R.S.; Shah, A.N.; Tahir, M.B.; Umair, M.; Nawaz, M.; Ali, A.; Ercisli, S.; Abdelsalam, N.R.; Ali, H.M.; Yang, S.H. Recent trends and advances in additive-mediated composting technology for agricultural waste resources: A comprehensive review. *ACS Omega* **2024**, *9*, 8632–8653. [\[CrossRef\]](#) [\[PubMed\]](#)
- British Pharmacopoeia Commission. *How to Use the British Pharmacopoeia*; British Pharmacopoeia Commission: London, UK, 2022.
- Council of Europe. *European Directorate for the Quality of Medicines & HealthCare (EDQM)*; Council of Europe: Strasbourg, France, 2024.
- ISO 10390:2021; Soil, Treated Biowaste and Sludge—Determination of pH. International Organization for Standardization: Geneva, Switzerland, 2021.
- International Organization for Standardization. *ISO Technical Committee 282: Water Reuse—Activities and Standardisation Updates*; International Organization for Standardization: Geneva, Switzerland, 2023.
- Li, X.; Zhang, Y.; Chen, Z. Biological and chemical variability in compost sources requires statistical tolerance ranges. *Waste Manag.* **2022**, *152*, 30–42. [\[CrossRef\]](#) [\[PubMed\]](#)
- Roy, D.; Gunri, S.K.; Kundu, C.K.; Bandyopadhyay, P.K. Rapid composting of groundnut residues through novel microbial consortium: Evaluating maturity, stability, and microbial activity. *Curr. Res. Microb. Sci.* **2024**, *7*, 100277. [\[CrossRef\]](#) [\[PubMed\]](#)
- Chen, K.; Khan, N.; Wadewitz, P.; Lamichhane, P.; Ahmed, M.B.; Kwong, P.; Hessel, V. Pros and cons of nitrogen replenishment in compost, augmented by natural acidity regulators, agri-buffering adjuvants, and grease trap waste. *Bioresour. Technol. Rep.* **2026**, *34*, 102729. [\[CrossRef\]](#)
- Chen, K.; Khan, N.; Ahmed, M.B.; Kwong, P.; Hessel, V. Environmental and Ecosystem Effects, Risk Assessment, and Mitigation Strategies for Advanced Composting. In *Compost Science & Utilization*; Taylor & Francis Group: Adelaide, AU, Australia, 2026; pp. 1–34. [\[CrossRef\]](#)

24. Amidon, G.L.; Lennernas, H.; Shah, V.P.; Crison, J.R. A theoretical basis for a biopharmaceutical drug classification: The correlation of in vitro drug product dissolution and in vivo bioavailability. *Pharm. Res.* **1995**, *12*, 413–420. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Khalid, F.; Hasan, S.M.F.; Mushtaque, M.; Noor, R.; Ghayas, S.; Muhammad, I.; Hassan, F. Comparative analysis of BCS based biowaiver protocols to validate equivalence of a multisource product. *Afr. J. Pharm. Pharmacol.* **2020**, *17*, 212–220. [\[CrossRef\]](#)
26. Firoozi, A.A.; Firoozi, A.A.; Oyejobi, D.O.; Avudaiappan, S.; Flores, E.S. Emerging trends in sustainable building materials: Technological innovations, enhanced performance, and future directions. *Results Eng.* **2024**, *24*, 103521. [\[CrossRef\]](#)
27. U.S. Food and Drug Administration. *Guidance for Industry: PAT—A Framework for Innovative Pharmaceutical Development, Manufacturing, and Quality Assurance*; U.S. Food and Drug Administration: Rockville, MD, USA, 2004.
28. International Council for Harmonisation. *ICH Harmonised Tripartite Guideline: Pharmaceutical Development Q8(R2)*; International Council for Harmonisation: Geneva, Switzerland, 2009.
29. Ojha, A.; Bhargava, S. International council for harmonisation (ICH) guidelines. In *Regulatory Affairs in the Pharmaceutical Industry*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 47–74.
30. Houson, I.; Siddique, H.; Chong, M.W.S.; Robertson, M.; Turner, A.J.; Nordon, A.; Osman, A.; Galindo, A.; Dunn, A.S.; Johnston, B.; et al. Quality by digital design in action: A workflow for crystallisation and isolation. *Int. J. Pharm.* **2025**, *686*, 126343. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Stehouwer, R.; Cooperband, L.; Rynk, R.; Biala, J.; Bonhotal, J.; Antler, S.; Lewandowski, T.; Nichols, H. Chapter 15—Compost characteristics and quality. In *The Composting Handbook*; Rynk, R., Ed.; Academic Press: Cambridge, MA, USA, 2022; pp. 737–775.
32. Gómez-Brandón, M.; Lazcano, C.; Domínguez, J. The evaluation of stability and maturity during the composting of organic wastes: A review. *Waste Manag. Res.* **2008**, *26*, 456–464. [\[CrossRef\]](#)
33. Aspray, T.J. Physical Contaminant Testing of Composts. *BioCycle* **2016**, *57*, 56–58.
34. Haug, R.T. *The Practical Handbook of Compost Engineering*; CRC Press: Boca Raton, FL, USA, 1993.
35. Prasad, M.; Foster, P. Comprehensive evaluation and development of Irish compost and digestate standards for heavy metals, stability and phytotoxicity. *Environments* **2023**, *10*, 166. [\[CrossRef\]](#)
36. ISO 11277:2018; Soil Quality—Determination of Particle Size Distribution in Mineral Soil Material—Method by Sieving and Sedimentation. International Organization for Standardization: Geneva, Switzerland, 2018.
37. Ouelid Lhaj, M.; Moussadek, R.; Mouhir, L.; Mdarhri Alaoui, M.; Sanad, H.; Iben Halima, O.; Zouahri, A. Assessing the evolution of stability and maturity in co-composting sheep manure with green waste using physico-chemical and biological properties and statistical analyses: A case study of botanique garden in rabat, Morocco. *Agronomy* **2024**, *14*, 1573. [\[CrossRef\]](#)
38. Agnew, J.M.; Leonard, J.J. The Physical Properties of Composts: A Review. *Compost. Sci. Util.* **2013**, *11*, 238–264.
39. US Composting Council. *Test Methods for the Examination of Composting and Compost (TMECC)*; US Composting Council: Bethesda, MD, USA, 2018.
40. Ministry of Agriculture, Forestry and Fisheries (MAFF). *Fertilizer Control Act*; Ministry of Agriculture, Forestry and Fisheries (MAFF): Tokyo, Japan, 2012.
41. ISO 11465:1993; Soil Quality—Determination of Dry Matter and Water Content on a Mass Basis—Gravimetric Method. International Organization for Standardization: Geneva, Switzerland, 1993.
42. European Compost Network. European Compost Network Activities and Quality Assurance Initiatives. Available online: <https://www.compostnetwork.info/> (accessed on 6 March 2026).
43. International Solid Waste Association. Global Guidelines for Organic Waste Management and Composting Systems. Available online: <https://www.iswa.org/> (accessed on 6 March 2026).
44. Sullivan, D.M.; Miller, R.O. Compost quality attributes, measurements, and variability. In *Compost Utilization in Horticultural Cropping Systems*; Stofella, P.J., Kahn, B.A., Eds.; CRC Press: Boca Raton, FL, USA, 2001; pp. 95–120.
45. National Organic Standards Board. *Compost Definition and Practice Standard Update*; United States Department of Agriculture (USDA), Agricultural Marketing Service: Washington, DC, USA, 2024.
46. Ramsey, M.H.; Ellison, S.L.R.; Rostron, P. *Measurement Uncertainty Arising from Sampling: A Guide to Methods and Approaches*; Eurachem: Bucharest, Romania, 2019.
47. ISO 16072:2002; Soil Quality—Laboratory Methods for Determination of Microbial Soil Respiration. International Organization for Standardization: Geneva, Switzerland, 2002.
48. BS EN 13040:2007; Soil Improvers and Growing Media—Sample Preparation for Chemical and Physical Tests, Determination of Dry Matter Content, Moisture Content and Laboratory Compacted Bulk Density. British Standards Institution: London, UK, 2008. [\[CrossRef\]](#)
49. International Organization for Standardization. *General Requirements for the Competence of Reference Material Producers*; International Organization for Standardization: Geneva, Switzerland, 2016.
50. International Organization for Standardization. *Reference Materials—Approaches for Characterization and Assessment of Homogeneity and Stability*; International Organization for Standardization: Geneva, Switzerland, 2024.

51. Boldrin, A.; Andersen, J.K.; Christensen, T.H.; Favoino, E.; Hogg, D. Composting and compost utilization: Accounting of greenhouse gases and global warming contributions. *Waste Manag. Res.* **2009**, *27*, 800–812. [[CrossRef](#)] [[PubMed](#)]
52. BS EN 12579:2013; Soil Improvers and Growing Media—Sampling. British Standards Institution: London, UK, 2013.
53. ISO 18400-105:2017; Soil Quality—Sampling—Part 105: Packaging, Transport, Storage and Preservation of Samples. International Organization for Standardization: Geneva, Switzerland, 2017.
54. ISO/IEC 17043:2023; Conformity Assessment—General Requirements for Proficiency Testing. International Organization for Standardization: Geneva, Switzerland, 2023.
55. ISO 19115-1:2014; Geographic Information—Metadata—Part 1: Fundamentals. International Organization for Standardization: Geneva, Switzerland, 2014.
56. Vaneekhaute, C.; Walling, E.; Rivest, S.; Belia, E.; Chartrand, I.; Fortin, F.; Mostafavi, M.A. Towards an integrated decision-support system for sustainable organic waste management (optim-O). *npj Urban Sustain.* **2021**, *1*, 27. [[CrossRef](#)]
57. Manono, B. Compost Quality and Application Rate as Drivers of Soil Health, Nutrient Cycling, and Crop Performance: A Critical Review and Practical Rate-Design Framework. *Nitrogen* **2026**, *7*, 58. [[CrossRef](#)]
58. Horn, A.L.; Düring, R.-A.; Gäth, S. Comparison of decision support systems for an optimised application of compost and sewage sludge on agricultural land based on heavy metal accumulation in soil. *Sci. Total Environ.* **2003**, *311*, 35–48. [[CrossRef](#)] [[PubMed](#)]
59. Queensland Department of Environment and Science. *Guideline: Best Practice Environmental Management—Environmentally Relevant Activity 53(a) Organic Material Processing by Composting*; Queensland Government: Brisbane, QLD, Australia, 2021.
60. Huzir, N.; Asmadi, A.; Rosly, M.; Tamunaidu, P.; Amin, A. Composting as a pathway for organic waste valorization: Substrate performance, process strategies, and quality benchmarks. *J. Mater. Cycles Waste Manag.* **2026**, *28*, 815–833. [[CrossRef](#)]
61. Gutierrez-Lopez, J.; McGarvey, R.G.; Costello, C.; Hall, D.M. Decision Support Frameworks in Solid Waste Management: A Systematic Review of Multi-Criteria Decision-Making with Sustainability and Social Indicators. *Sustainability* **2023**, *15*, 13316. [[CrossRef](#)]
62. Kandaiah, R.; Ravindran, A.; Panneerselvan, L.; Manivannan, A.C.; Kulanthaisamy, M.; Sobhani, Z.; Bhagwat-Russell, G.; Palanisami, T. A comprehensive analysis and risk evaluation of microplastics contamination in Australian commercial plant growth substrates: Unveiling the invisible threat. *J. Hazard. Mater.* **2024**, *480*, 136310. [[CrossRef](#)] [[PubMed](#)]
63. Nie, K.; McWright, L.; Rothwell, J.G.; Mondragon-Becerra, M.; Malal, H.; Lazcano, C.; Geisseler, D.; Scott, L.; Elliott Campbell, J.; Gomez-Ortega, J.; et al. cMicrobial Food Safety Risk in Finished Soil Amendment: A Statewide Cross-sectional Study of Organic Waste Processing Systems in California. *J. Food Prot.* **2026**, *89*, 100844. [[CrossRef](#)] [[PubMed](#)]
64. Rentizelas, A.; Georgiou, P.N.; Giannopoulos, D.; Stavrogiannis, C.; Papadakis, T.; Christou, I.T.; Psathas, F.; Anastasopoulos, D. A novel decision support system for designing and assessing phytoremediation-to-biofuel value chains. *Biofuels Bioprod. Biorefining* **2025**, *19*, 1014–1029. [[CrossRef](#)]
65. Meyer, S.; Genesio, L.; Vogel, I.; Schmidt, H.-P.; Soja, G.; Someus, E.; Shackley, S.; Verheijen, F.G.; Glaser, B. Biochar standardization and legislation harmonization. *J. Environ. Eng. Landsc. Manag.* **2017**, *25*, 175–191. [[CrossRef](#)]
66. Romero-Perdomo, F.; González-Curbelo, M.Á. Integrating multi-criteria techniques in life-cycle tools for the circular bioeconomy transition of agri-food waste biomass: A systematic review. *Sustainability* **2023**, *15*, 5026. [[CrossRef](#)]
67. European Environment Agency. *Soil Health Dashboard*; European Environment Agency: Copenhagen, Denmark, 2023.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.