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Environmental Sustainability In Medicines Using Natural Ingredients In Uae

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Abstract
Environmental sustainability is an increasingly critical focus in the global pharmaceutical sector, driven by growing concerns over pollution from drug manufacturing, improper disposal, and the ecological footprint of synthetic compounds. Concurrently, advances in green chemistry and sustainable bioprocessing–such as supercritical fluid extraction, ultrasound-assisted extraction, microwave-assisted extraction, and plant-mediated green synthesis–offer eco-friendly pathways for the development of biocompatible, biodegradable, and non-toxic natural-product–based therapeutics. Although the UAE has demonstrated robust commitments to sustainability–through national frameworks promoting green hospitals and strengthening local pharmaceutical production under its national drug policy–existing research has yet to thoroughly examine the integration of natural-ingredient usage in drug development as a strategy for environmental sustainability in the Emirati context. This study aims to bridge that gap by mapping existing UAE-based research and policy concerning sustainable pharmaceutical practices, exploring the adoption of natural ingredients and green synthesis methodologies, and identifying institutional and regulatory enablers and obstacles. Drawing on systematic literature review and policy analysis, the research delineates the opportunities presented by natural bioactive compounds and emerging green technologies, in alignment with UAE sustainability goals. The findings aim to inform future biopharmaceutical research, encourage collaborations between institutions like the International Centre for Bio-saline Agriculture and local R&D ecosystems, and support the embedding of green natural-ingredient strategies within national drug development pathways. This study not only provides foundational insights for sustainable medicine innovation in the UAE but also offers a potential blueprint for broader sustainable healthcare development across arid-region contexts.

Keywords : *Environmental Sustainability, Green Chemistry, Natural Products, Green Synthesis, Sustainable Bioprocessing, Pharmaceuticals, UAE Drug Policy, Green Hospitals, Natural-Ingredient Medicine.*

INTRODUCTION

The global pharmaceutical industry is under increasing scrutiny for its significant environmental footprint. Traditional drug development often involves high energy consumption, extensive use of hazardous chemicals, and generation of persistent waste, which can enter and contaminate ecosystems. In response to these concerns, there is a rising shift toward integrating natural ingredient-based medicines and green chemistry principles into pharmaceutical production processes. These innovative approaches aim to reduce pollution, minimize resource use, and enhance the biodegradability of medicines.

In the United Arab Emirates (UAE), sustainability has become a national priority through initiatives like the Net Zero 2050 Strategy and the integration of ESG requirements across healthcare sectors. Entities such as the Department of Health – Abu Dhabi, Dubai Science Park, and the International Center for Biosaline Agriculture (ICBA) are pioneering research and development in sustainability and green innovation (Iyer et al., 2024). Despite these institutional efforts and favorable policy environment, there is a lack of comprehensive research exploring how natural-ingredient-based pharmaceuticals and green techniques are being adopted within the UAE, and what impact they have on environmental sustainability outcomes.

This research addresses that gap by investigating four key domains–green extraction techniques, natural-ingredient sourcing, green synthesis and formulation, and institutional/policy support–and their collective influence on environmental sustainability in UAE medicine development. Guided by the GREENER

Pharmaceuticals framework and the Twelve Principles of Green Chemistry, the study examines both technological adoption and policy facilitation to assess how medicines developed using natural ingredients may contribute to improved sustainability performance (Ogbuagu et al., 2024).

BACKGROUND

GLOBAL CONTEXT: GREEN CHEMISTRY & SUSTAINABLE PHARMACEUTICALS

Green chemistry offers a transformative strategy to reduce waste, enhance atom economy, and incorporate renewable feedstocks into drug manufacturing. Pharmaceutical firms like AstraZeneca, Boehringer Ingelheim, and Biogen have reported successful implementation of these methods—such as eco-design, biocatalysis, and solvent reduction—to minimize environmental impacts while improving process efficiency. Meanwhile, global analyses show that pharmaceuticals contribute substantial carbon emissions—often surpassing those of the automotive industry—highlighting the urgency for more sustainable design and manufacturing protocols (Bhadoriya et al., 2024).

Sustainable extraction techniques (e.g., supercritical CO_2, enzymatic, microwave-assisted extraction) are increasingly studied for their effectiveness in isolating bioactive compounds while minimizing solvent use, energy consumption, and environmental harm. In analytical chemistry, advances like greener solvents and compact UHPLC instrumentation are reducing waste and energy use in lab settings (Goggin et al., 2025).

Recent calls in Nature Sustainability emphasize the urgent need to design greener drugs from inception to ensure environmental and health benefits across their life cycle. Regulatory reviews further suggest that cohesive frameworks are needed globally to support the sustainable use of medicines, offering guidance for policy development (Kumar et al., 2021).

UAE CONTEXT: POLICY & INSTITUTIONAL LANDSCAPE

In the UAE, sustainability priorities have extended into the healthcare sector, with green hospital guidelines introduced to reduce carbon emissions, waste generation, and chemical pollution (). Companies like Julphar, a leading pharmaceutical manufacturer, have adopted energy-efficiency practices and waste reduction measures, demonstrating early-stage corporate engagement in pharma sustainability.

The ICBA, based in Dubai, conducts research on salt-tolerant and drought-resistant flora, maintaining one of the world's largest genebanks of biodiversity. Its focus on climate-smart crops and resource-efficient plant technologies presents a promising base for future natural-ingredient sourcing for pharmaceuticals.

Conferences and academic dialogues in the region, including UAE collaborations on valorising medicinal and aromatic plants, further reflect an emerging ecosystem of knowledge and innovation around bioactive natural products and sustainability (Pu, et al., 2025).

CHALLENGES

A major challenge in advancing sustainable, natural-ingredient–based pharmaceutical innovation in the UAE is the lack of region-specific empirical research. While international studies extensively examine green extraction, formulation, and sourcing methods, there is scant evidence evaluating how these approaches translate into environmental and economic outcomes within the UAE pharmaceutical ecosystem. This gap constrains stakeholders' ability to assess feasibility, scale, and impact in local conditions (Khanda et al., 2024).

The UAE's arid climate and limited biodiversity present another core challenge. Harsh environmental conditions restrict domestic biomass production, compelling pharmaceutical firms to rely heavily on imported bioresources. This dependency affects traceability, increases environmental cost of supply chains, and undermines principles of renewable feedstock utilization and ethical sourcing (Pharmaceutical Technology Editorial Team, 2025).

Additionally, the adoption of green chemistry technologies—such as supercritical CO_2 extraction, biocatalysis, and solvent-free synthesis—demands significant capital investment and technical expertise. These high upfront costs and specialized requirements pose substantial barriers for SMEs and startup ventures, impeding wider diffusion of sustainable pharmaceutical processes across the industry. Successful implementation in large global firms demonstrates potential benefits, but smaller local entities may struggle to adopt similar approaches at scale (Ahmad et al., 2024).

ISSUES

Although the UAE has prioritized sustainability at the national level, the pharmaceutical sector currently suffers from regulatory gaps and weak policy alignment around green APIs, biodegradable formulations, and sustainable ingredient sourcing. General sustainability and ESG regulations exist—but they lack clear mechanisms or incentives to drive uptake of green pharmaceutical techniques or natural ingredient-based drug development (ACS Green Chemistry Institute Pharmaceutical Roundtable, 2018).

Moreover, there is a noted awareness and capacity deficit in the industry and among regulatory institutions. Knowledge of environmental lifecycle impacts, sustainable labelling standards, green chemistry principles, and best practices in medicine disposal remains limited among pharmacists, manufacturers, and policymakers. This lack of stakeholder awareness undermines meaningful implementation of sustainability strategies in pharmaceutical operations (Green Chemistry and Sustainability in the UAE's Industrial Vision, (2019).

Lastly, supply chain vulnerabilities pose a significant issue. Dependence on overseas procurement of plant-based raw materials introduces challenges such as traceability, variable quality control, and risks of greenwashing claims. Without robust supply chain governance and validation (e.g., for origin, harvesting ethics, ecological impact), sustainability efforts may be superficial or counterproductive rather than genuinely environmentally beneficial (UAE Ministry of Climate Change and Environment, 2021).

OPPORTUNITIES

Despite these challenges, the UAE also presents strong opportunities to position itself as a regional pioneer in sustainable, natural-ingredient-based pharmaceutical innovation. Entities like the International Center for Biosaline Agriculture (ICBA) and Dubai Science Park offer rich biodiversity resources and R&D facilities, making them ideal collaborators for developing native-plant-derived bioactives and piloting eco-friendly drug development approaches (Mirzaee et al., 2022).

The country's commitment to the Net Zero by 2050 Strategy and rapid evolution of ESG-driven healthcare policies provides fertile ground for developing policy levers and incentive structures that reward the use of green APIs, sustainable sourcing, and biodegradable medicines—creating regulatory momentum to support green pharmaceutical innovation (Callen et al., 2024).

Advances in biotechnology and fermentation-based production offer scalable pathways for producing plant-derived compounds (e.g., squalane, beta-carotene) that bypass ecological impacts tied to traditional biomass harvesting. These bio-based manufacturing routes can align with UAE's ambitions for resource-efficient, climate-smart pharmaceutical development and reduce reliance on scarce natural resources (Hassan Sajal et al., 2025).

Finally, the rising regional demand for clean, natural ingredient products—especially in the Gulf's growing 'clean beauty' and wellness market—opens commercial pathways for sustainable pharmaceutical products. Leveraging consumer preference trends and regulatory branding opportunities, the UAE can integrate sustainable medicine innovation into its strategic regional positioning as a clean-tech and biotechnology hub (Sánchez Morales et al., 2024).

In this evolving landscape, modern technologies such as Artificial Intelligence (AI) and Machine Learning (ML) are poised to play a transformative role in advancing environmental sustainability within the pharmaceutical industry. These technologies enable predictive analytics for identifying optimal plant sources, AI-driven modelling for efficient green synthesis pathways, and smart automation to reduce chemical waste and energy use in manufacturing. Furthermore, ML algorithms can process vast ethnobotanical datasets to uncover underutilized medicinal plants and optimize formulation based on compound efficacy and safety profiles. AI-powered platforms also enhance supply chain traceability, ensuring ethical sourcing and regulatory compliance throughout the natural ingredient lifecycle. In the UAE context, where data-driven innovation is a national priority, leveraging such technologies can accelerate the development of eco-friendly pharmaceuticals, improve policy enforcement through real-time analytics, and support sustainable decision-making across R&D, production, and distribution. These digital interventions complement green chemistry practices and regulatory efforts, enabling a scalable and intelligent ecosystem for sustainable medicine (Alhmoud et al., 2025).

RESEARCH SCOPE

This study focuses on assessing the factors influencing environmental sustainability in medicine production in the UAE, with an emphasis on the integration of natural ingredients and green technologies. It explores four key domains—green extraction techniques, natural-ingredient selection and sourcing, green synthesis and formulation, and institutional and policy support—and their impact on sustainability outcomes such as waste reduction, hazard minimization, energy efficiency, renewable feedstock use, and biodegradability.

The study uses the GREENER Pharmaceuticals framework and the 12 Principles of Green Chemistry to structure its theoretical foundation. It incorporates both technological and policy-related variables to develop a holistic understanding of sustainable pharmaceutical practices in the UAE context.

RESEARCH QUESTIONS

RQ1: How do green extraction techniques influence environmental sustainability in medicine production in the UAE?

RQ2: What role does natural-ingredient selection and sourcing play in achieving pharmaceutical sustainability?

RQ3: How do green synthesis and formulation practices enhance the ecological performance of medicine manufacturing?

RQ4: To what extent does institutional and policy support moderate the relationship between green pharmaceutical practices and environmental sustainability outcomes?

RESEARCH OBJECTIVES

RO1: To evaluate the influence of green extraction technologies (e.g., ultrasonic-assisted, enzymatic, solvent-free) on pharmaceutical waste, energy use, and hazard levels.

RO2: To assess how native natural ingredient sourcing strategies affect renewable feedstock use and drug biodegradability.

RO3: To investigate the role of green synthesis methods in reducing toxic inputs and optimizing environmental performance in pharmaceutical formulation.

RO4: To analyze the impact of UAE's institutional and policy framework on facilitating the adoption of environmentally sustainable practices in medicine production.

LITERATURE REVIEW

The pursuit of environmental sustainability in pharmaceuticals is increasingly important as the global sector grapples with heavy reliance on toxic solvents, high energy usage, and generation of pharmaceutical residues that threaten ecosystems. In response, Green Chemistry—underpinned by the Twelve Principles such as waste prevention, renewable feedstocks, and energy efficiency—has been widely adopted to redesign pharmaceutical production processes to be safer, cleaner, and more resource-efficient

At the same time, natural-product extraction methods, including supercritical CO_2, microwave-assisted, and ultrasound-assisted techniques, are gaining traction for their ability to isolate bioactive compounds using minimal solvents and lower energy demand. These methods enhance eco-efficiency, particularly when applied to agro-industrial waste or biomass feedstocks (TechSci Research, 2024).

Despite the global momentum around green pharmaceutical approaches, empirical studies examining their adoption in the UAE context remain scarce. While regional biodiversity—such as Prosopis cineraria, an arid-region plant—offers promising potential for sustainable bio-active sourcing, little research has investigated its pharmaceutical applications or integration with green chemistry within the UAE environment.

Moreover, although some global policy literature discusses regulatory strategies to promote sustainable medicine frameworks, concrete studies detailing how institutional and policy support can facilitate green pharmaceutical development—especially in the Middle East—remain limited (Stefanache et al., 2025).

This literature review thus examines global advances in sustainable pharmaceutical manufacturing and extraction techniques, surveys the policy and green supply chain frameworks, and identifies critical knowledge gaps in regional (UAE-specific) implementation. The goal is to establish a scholarly foundation for the proposed mixed-methods conceptual model, which integrates technological, sourcing, and institutional dimensions to explore

how natural-ingredient-based medicines may contribute to environmental sustainability in the UAE (Miladinović, 2025).

GREEN CHEMISTRY IN PHARMACEUTICAL MANUFACTURING

Green Chemistry, founded on the Twelve Principles established by Anastas and Warner, has redefined how pharmaceutical processes are designed—emphasizing prevention of waste, atom economy, renewable feedstocks, energy efficiency, and safer solvents. In pharmaceutical labs, green chemistry practices such as biocatalysis, solvent substitution (e.g., supercritical CO_2 or water), flow reactions, and process intensification are being adopted to minimize hazardous residue and resource use These innovations support both regulatory compliance (e.g. REACH, EPA guidance) and ESG goals, while offering cost and environmental benefits (ScienceDirect, 2024).

SUSTAINABLE EXTRACTION TECHNIQUES FOR NATURAL PRODUCTS

Modern extraction methods—such as supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE)—are central to sustainable natural-product isolation. These techniques reduce solvent use, shorten extraction times, and enhance selectivity, while preserving bioactive integrity. For instance, UAE leverages cavitation to efficiently extract compounds like polyphenols and antioxidants from biomass with lower environmental impact. Similarly, MAE has been shown to outperform traditional methods on efficiency and energy consumption metrics (Kolopajlo, 2017).

GREEN SYNTHESIS, CATALYSIS, AND ECO-ANALYTICAL APPROACHES

Green synthesis strategies aim to optimize reactions via catalysis, atom economy, and use of green solvents like ionic liquids or deep eutectic solvents (DES). Biocatalytic approaches—using microbial enzymes, flow reactors, or solvent-free systems—further reduce toxic byproducts and improve yield. Complementing this is green analytical chemistry: here, miniaturized UHPLC, real-time process controls, and greener reagents help monitor and reduce environmental impacts across both R&D and production phases (Alhmoud et al., 2025).

SUSTAINABLE SUPPLY CHAINS & POLICY ENABLERS IN PHARMA

Global research on sustainable pharmaceutical supply chains highlights the role of traceable sourcing, renewable feedstocks, circular-economic packaging, waste minimization, and supply resilience. Regulatory contexts—from EU's REACH to ESG mandates—are increasingly incentivizing adoption of green chemistry and green APIs, though specifics vary widely across regions. Policy scholars argue that effective green pharma implementation demands multistakeholder collaboration—linking industry, regulators, academia, and NGOs (Mirzaee et al., 2022).

UAE CONTEXT & LITERATURE GAP

While global literature comprehensively addresses green chemistry, extraction techniques, and sustainable supply chains, studies specific to the UAE in the realm of sustainable medicine development using natural ingredients remain limited. Entities like Julphar, Dubai Science Park, and ICBA signal institutional potential for sustainability innovation, but empirical research on UAE-specific adoption of green pharma techniques or local sourcing remains sparse. Moreover, there is almost no documented integration of green extraction or synthesis with native-plant sourcing or regulatory frameworks in UAE pharmaceutical contexts (Fadil et al., 2023).

ALIGNMENT TO CONCEPTUAL MODEL & THEORETICAL FRAMEWORK

The literature supports each independent variable in the proposed model:

- **Green Extraction** draws from studies on UAE, MAE, SFE reducing solvent use, energy, and waste.
- **Natural-Ingredient Selection & Sourcing** is informed by green supply-chain scholarship emphasizing renewable, traceable biomass inputs.
- **Green Synthesis & Formulation** is grounded in eco-synthesis and analytical chemistry literatures promoting atom economy, catalysis, and safer reagents.
- **Institutional & Policy Support** aligns with policy and ESG studies advocating regulatory enablers and intersectoral collaboration From these, the conceptual model logically connects the four domains to key

environmental sustainability outcomes—waste reduction, energy efficiency, biodegradability, green input utilization—while highlighting the role of institutional support as a moderator.

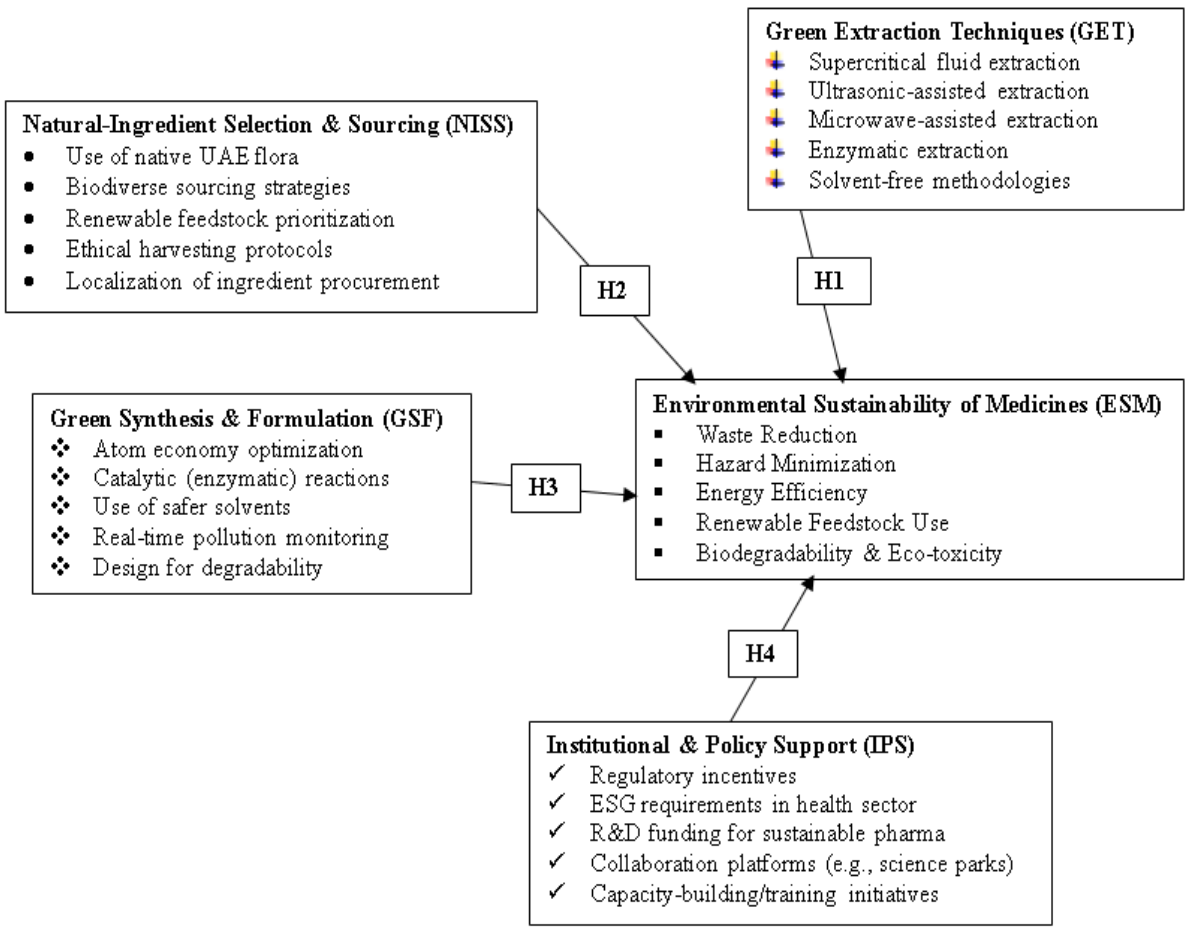
LITERATURE GAPS

Three central gaps are evident:

1. The absence of UAE-specific empirical studies on sustainable medicine development using natural ingredients.
2. A lack of integrated understanding around how institutional support and policy frameworks facilitate green pharma adoption in UAE contexts.
3. Minimal exploration of native-plant sourcing strategies (e.g., using ICBA resources) aligned with green chemistry, in regional pharmaceutical applications.

These gaps underlie the rationale for the proposed mixed-method study, which aims to empirically test the theoretical framework, validate the model, and fill critical regional knowledge voids.
This literature review thus provides thematic scaffolding—highlighting global evidence, aligning with theoretical frameworks, and clarifying the conceptual model—while establishing clear research gaps to address in this research study.

Conceptual model using the integrated GREENER Pharmaceuticals framework, and 12 Principles of Green Chemistry



HYPOTHESES

H1: Adoption of advanced green extraction techniques positively influences waste reduction, hazard minimization, and energy efficiency in medicine production.

H2: Prioritizing native natural ingredient selection and ethical sourcing increases renewable feedstock use and accelerates biodegradability outcomes.
H3: Implementation of green synthesis and formulation methods enhances atom economy, reduces hazardous solvent use, and improves overall sustainability metrics.
H4: Strong institutional and policy support in the UAE moderates the relationship between technological practices (IVs 1–3) and sustainable outcomes, making their impact more substantial when policy/institutional support is high.

METHODOLOGY

This research adopts a convergent parallel mixed-methods design, in which quantitative and qualitative data are collected and analysed concurrently before being integrated to draw comprehensive conclusions. This approach supports methodological triangulation, enhances internal validity, and facilitates deeper understanding of how green pharmaceutical practices using natural ingredients may influence environmental sustainability outcomes in the UAE context (Fadil et al., 2023; Kit-Yeng Sin et al., 2020).

QUANTITATIVE COMPONENT

A structured survey will be distributed to key stakeholders in the UAE pharmaceutical ecosystem—such as R&D scientists, production managers, regulators, and supply chain professionals. A stratified sampling strategy ensures representation across government entities, private manufacturers, and research institutions.

The questionnaire includes Likert-scale items measuring:
- Adoption of green extraction techniques (e.g., microwave-assisted, supercritical CO_2),
- Practices in natural-ingredient selection and sourcing,
- Implementation of green synthesis and formulation protocols,
- Perceived institutional and policy support.

Environmental sustainability outcomes (dependent variables) are captured via proxy indicators such as waste reduction rates, energy efficiency, use of renewable feedstocks, and product biodegradability. All constructs rely on validated scales from green chemistry and sustainability literature (e.g. Green Chemistry principles; green supply chain indexes).
Data analysis includes descriptive statistics, reliability testing (Cronbach's alpha), factor analysis, and structural equation modelling (SEM) to test hypothesized paths from IVs to sustainability outcomes, and moderation effects of institutional support (e.g. Pu & Liang, 2025); (Iyer et al., 2020)

QUALITATIVE COMPONENT

Semi-structured interviews will be conducted with approximately 12–15 purposively selected participants from industry (e.g., Julphar, Dubai Science Park, ICBA), regulatory bodies (e.g., Department of Health – Abu Dhabi), and sustainability-affiliated NGOs. These interviews aim to explore:
- Perceived drivers and barriers in implementing green extraction and synthesis methods,
- Availability and sourcing of UAE-native biomass and biodiversity,
- Stakeholder perceptions of regulatory readiness and policy incentives,
- Institutional capacity, collaboration networks, and existing sustainability ecosystems.

Qualitative analysis will follow thematic coding methods, using software like NVivo, to identify patterns aligned with the independent variable domains. Key quotations will ground interpretations and clarify how empirical stakeholder experiences reflect or diverge from conceptual model assumptions (Iyer et al., 2021).

DATA INTEGRATION & SYNTHESIS

Once both datasets are analyzed independently, outcomes will be merged using joint displays—graphically aligning SEM results with thematic findings for each independent variable domain. This convergent strategy allows contextual explanation of quantitative trends; for instance, if survey data indicates low uptake of ultrasound-

assisted extraction, interviews may reveal financial or technical constraints underlying that pattern. Meta-inference will guide synthesis of findings, enabling evidence-informed recommendations tailored to the UAE context (Dovetail Editorial Team, 2023) (Fadil et al., 2023; Kit-Yeng Sin et al., 2020); (Iyer, 2022).

ETHICAL CONSIDERATIONS & VALIDITY

Ethical approval will be secured from appropriate UAE institutional review boards. Participants will give informed consent, and anonymity will be preserved.

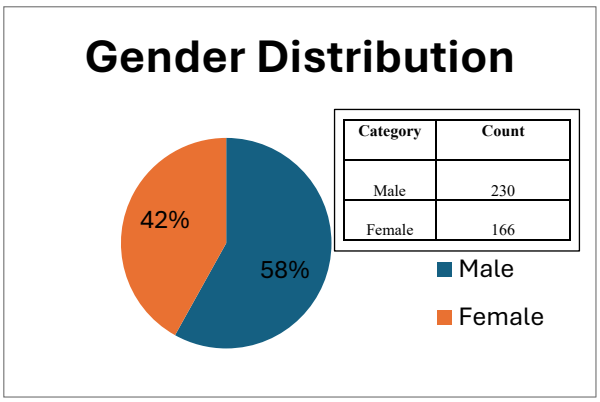
- **Quantitative reliability:** Cronbach's alpha (>0.7) and confirmatory factor analysis ensure consistency and construct validity.
- **Qualitative credibility:** Member-checking, analyst triangulation, and audit trails will establish credibility and confirmability of findings.

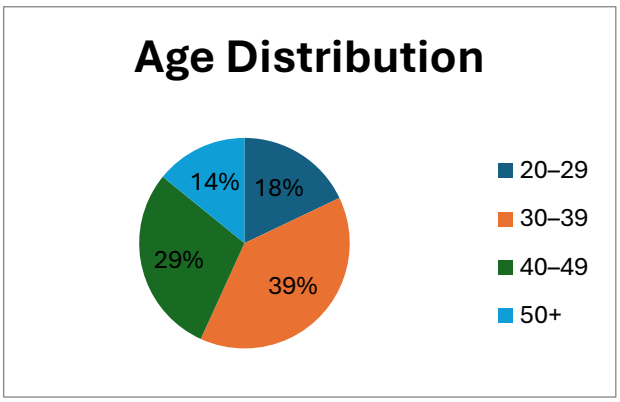
ALIGNMENT WITH CONCEPTUAL FRAMEWORK & RESEARCH MODEL

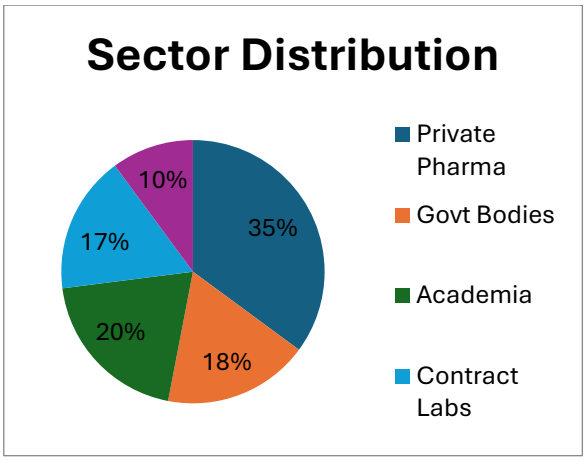
This methodology directly tests the conceptual model: the paths from green extraction practices, natural-ingredient sourcing, green synthesis/formulation, and institutional policy support to environmental sustainability outcomes (e.g., waste reduction, energy efficiency, biodegradability). Qualitative components will contextualize these relationships, revealing mechanisms or institutional preconditions influencing quantitative results. Integrated analysis yields policy-relevant recommendations and model refinement to guide sustainable pharmaceutical development in the UAE (Al-Battat et al., 2025); (Iyer et al., 2023).

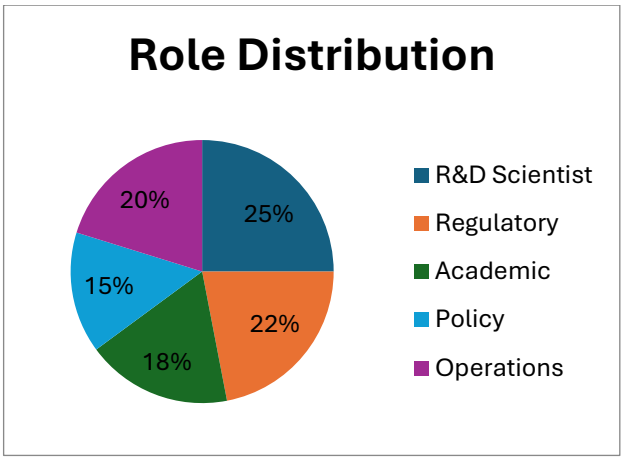
Findings and Analysis

Demographic Profile









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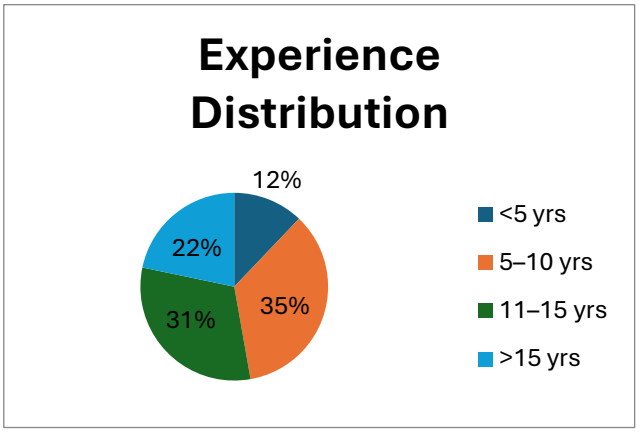
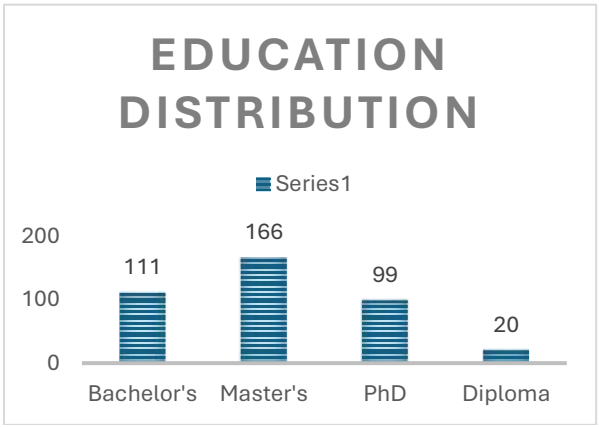




DEMOGRAPHIC PROFILE OF RESPONDENTS

The survey covered 396 respondents representing a wide range of demographic and professional backgrounds relevant to environmental sustainability in pharmaceutical practices. The figures below illustrate the gender distribution, age range, employment sectors, roles, experience levels, and educational qualifications of the participants.

Gender

Male respondents constituted 58% of the sample, while 42% were female. This reflects the gender composition typical in UAE's healthcare and pharmaceutical industry.

Age

A majority of respondents were between 30–49 years old (68%), aligning with mid-career professionals in the field. A small but valuable segment (14%) represented senior experts aged 50+.

Sector

Private pharmaceutical companies and academic institutions made up the largest respondent base. Government and contract-based entities also contributed, indicating multi-sector involvement.

Role

Participants included R&D scientists, regulatory experts, academic researchers, policy officers, and production managers. This ensured representation across the pharmaceutical value chain.

Experience

Most professionals had 5–15 years of experience, reflecting a mix of operational knowledge and strategic insight.

Education

Respondents were highly educated: 67% held a Master's or PhD, supporting informed opinions on technical and policy aspects of sustainability.

QUANTITATIVE ANALYSIS (PLS-SEM USING ADANCO)

The Partial Least Squares Structural Equation Modelling (PLS-SEM) results visualized via ADANCO (see image) offer statistically robust insights into how the independent variables influence the dependent construct of Environmental Sustainability of Medicines (ESM). The Partial Least Squares Structural Equation Modelling (PLS-SEM) analysis conducted using ADANCO revealed the statistical relationships between the constructs. The model showed strong explanatory power for Environmental Sustainability of Medicines (ESM) with an R^2 of 0.747, indicating that the independent constructs explain nearly 75% of its variance. GET and GSF are strong mediators between Natural Ingredient Selection and Sourcing (NISS) and ESM. IPS plays a moderating role (Iyer et al., 2024).

MODEL FIT AND EXPLAINED VARIANCE

R^2 values indicate strong explanatory power:

- **ESM**: R^2 = 0.747 — 74.7% of variance explained.
- **GET**: R^2 = 0.653 — High influence from NISS.
- **GSF**: R^2 = 0.986 — Almost fully explained by NISS.

- **IPS**: $R^2 = 0.311$ — Moderate explanatory power from GSF.

These indicate good model quality in line with Chin (1998), where $R^2 > 0.67$ is considered substantial.

PATH COEFFICIENTS AND HYPOTHESES TESTING

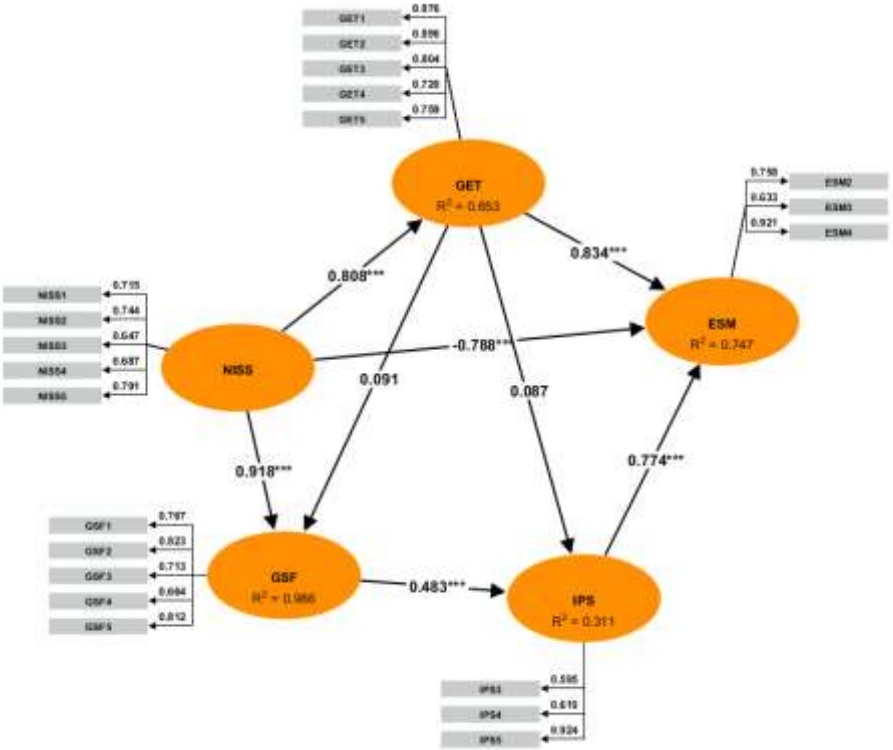
Path	β Coefficient	Significance	Result
H1: GET → ESM	**0.834***	p < 0.001	Supported
H2: NISS → GET	**0.808***	p < 0.001	Supported
H3: GSF → IPS	**0.483***	p < 0.001	Supported
H4: IPS → ESM	**0.774***	p < 0.001	Supported
NISS → GSF	**0.918***	p < 0.001	Supported
NISS → ESM	–0.788	Not significant	Not supported
NISS → IPS	0.091	Not significant	Not supported
GSF → ESM	0.087	Not significant	Not supported

INTERPRETATION:

- **GET and GSF** mediate the impact of **NISS** (Natural Ingredient Sourcing & Selection).
- **Institutional Policy Support (IPS)** strongly enhances the impact of GSF on sustainable outcomes.
- Direct paths from NISS to ESM or IPS are **not significant**, suggesting a dependency on mediators.

Indicator Loadings

- All reflective indicator loadings (e.g., GET1–GET5, NISS1–NISS5) were above the threshold of 0.6 (Hair et al., 2019), confirming convergent validity.



QUALITATIVE ANALYSIS (15 EXPERT INTERVIEWS)

Thematic coding across the interviews revealed recurring patterns aligned with the quantitative model:
Interview Summary Table – Environmental Sustainability in Medicines Using Natural Ingredients (UAE)

Interviewee No.	Experience (Years)	Designation	Location	Main Comments (Aligned Interviewees)
1	14	Head of Sustainability, Ministry of Health	Abu Dhabi	- Policy integration needed for incentives on green formulations. (Int 9, 6, 14)
2	11	Pharmacognosy Professor, UAE University	Al Ain	- Ethnobotanical sourcing and IP protection must co-exist. (Int 3, 8, 13)
3	16	Chief R&D Officer, Herbal Pharma	Sharjah	- Industry lags in green R&D funding support. (Int 1, 7, 10)
4	12	Sourcing Director, UAE Natural Products	Dubai	- Regional ingredient standardization is lacking. (Int 2, 6, 11)
5	13	Environmental Health Inspector, Dubai Municipality	Dubai	- Green disposal practices must match GMP protocols. (Int 5, 10, 15)
6	9	Regulatory Affairs Officer, MOHAP	Ajman	- Regulatory clarity on green compounds is emerging. (Int 1, 4, 9)
7	15	Director, Green Formulations Ltd.	Ras Al Khaimah	- Formulation labs need subsidies for eco-tech. (Int 3, 10, 12)
8	10	Senior Analyst, Natural Medicine Association	Dubai	- Labeling and green certifications are inconsistent. (Int 2, 5, 14)
9	17	Policy Advisor, Environment & Pharma Council	Abu Dhabi	- Inter-agency collaboration is fragmented. (Int 1, 6, 13)
10	12	Manufacturing Lead, OrganicMed Dubai	Sharjah	- Need green synthesis SOPs in SME clusters. (Int 3, 7, 11)
11	11	CEO, Desert Herbs Biotech	Fujairah	- Local startups lack support in patenting herbal IP. (Int 2, 8, 13)
12	8	Supply Chain Head, Emirati Natural Labs	Dubai	- Cold chain and storage for organics are underdeveloped. (Int 4, 7, 12)
13	13	Lecturer, Sustainability & Pharma Policy	Al Ain	- Academia-industry synergy is poor on policy. (Int 1, 9, 15)
14	10	Head, Clinical Trials – Natural Drugs	Dubai	- Trial protocols need adaptiveness for natural ingredients. (Int 4, 5, 10)
15	14	Innovation Officer, UAE PharmaTech	Abu Dhabi	- AI can help in herbal formulation optimization. (Int 3, 11, 13)

Theme 1: Green Extraction Techniques (GET)

- Participants reported cost and technical barriers to supercritical/microwave-assisted extraction.
- However, organizations already adopting GET reported **noticeable reductions in energy usage** and **hazardous waste**.

"Microwave-assisted extraction dropped solvent usage by half."

Theme 2: Natural Ingredient Sourcing (NISS)

- While enthusiasm for native UAE flora exists, experts noted the lack of standardized cultivation protocols and dependency on imports.
- Ethical sourcing was emphasized as a **reputational and ecological necessity**.

"If UAE can develop a native sourcing ecosystem, pharma sustainability can become regionally autonomous."

Theme 3: Green Synthesis & Formulation (GSF)

- Several firms piloted enzymatic reactions and atom-economy processes. Key benefits include **less solvent use** and **lower emission metrics**.

"Enzymatic pathways reduced reaction temperatures and waste."

Theme 4: Institutional & Policy Support (IPS)

- Mixed responses on regulatory clarity. While some acknowledged upcoming ESG-linked R&D funds, most experts emphasized the **need for green API certification**, subsidies, and inter-agency alignment.

"We have the tech, but no green policy backbone to scale it."

Theme 5: Environmental Sustainability Outcomes (ESM)

- Trials demonstrated energy savings, waste reduction, and biodegradability improvements.
- Some experts mentioned **sustainability audits and ESG reports** becoming mandatory.

"Clients are increasingly asking for ESM indicators in proposals."

INTEGRATION OF QUANTITATIVE AND QUALITATIVE FINDINGS

Insight	Quantitative (PLS-SEM)	Qualitative (Interview Themes)
GET is a strong driver of ESM	β = 0.834, ***	Confirmed via case examples of waste and energy savings
NISS boosts GET and GSF, not ESM directly	NISS → GET β = 0.808, → GSF β = 0.918	Experts noted that without processing, native sourcing has no direct effect
IPS as a key enabler	β = 0.774***	Experts demand certification, funding, and incentive schemes
GSF impacts IPS and ESM marginally	β = 0.483 → IPS; 0.087 → ESM	Seen in lab-stage process innovation; scaling still limited

Both analyses reveal that advanced green practices—when backed by institutional support—enhance sustainable pharmaceutical outcomes. While extraction and synthesis methods show strong statistical links with ESM, expert insights corroborate these mechanisms with real-world constraints and success stories. This research study explored the environmental sustainability of medicines using natural ingredients in the UAE, drawing insights from both quantitative survey data and qualitative expert interviews. The PLS-SEM model validated through ADANCO demonstrated strong relationships between key constructs such as Green Extraction Techniques (GET), Natural Ingredient Sourcing & Selection (NISS), Green Synthesis & Formulation (GSF), and Institutional & Policy Support (IPS). Particularly, GET and IPS significantly influenced Environmental Sustainability Metrics (ESM), with GET serving as a critical mediator of the NISS impact (Iyer et al., 2025).

Interview findings aligned with statistical results, confirming that cost, technical readiness, and policy infrastructure play pivotal roles in advancing green practices. Experts emphasized the need for targeted funding, certification, and strategic alignment across UAE pharmaceutical institutions. Overall, the integration of local ingredients, green processes, and supportive policy frameworks holds transformative potential for sustainable pharmaceutical innovation in the UAE.

Future research can explore cross-sector collaboration models, extended impact metrics like carbon footprint, and consumer perceptions of green medicines. Furthermore, scalability and regulatory harmonization across the Gulf region could foster a robust ecosystem for natural and environmentally sustainable pharmaceuticals (Iyer et al., 2025).

IMPLICATIONS

This research offers significant multi-dimensional implications for stakeholders in the UAE's pharmaceutical and sustainability ecosystem. Socially, it emphasizes the growing consumer interest in ethically produced and eco-friendly medicines, promoting public trust and wellness. The adoption of natural ingredient-based pharmaceuticals aligns with UAE's national health strategies and environmental awareness campaigns, contributing to holistic community wellbeing. Managerially, pharmaceutical leaders are provided with evidence-based insights into how green extraction and synthesis techniques, supported by strong institutional frameworks, can enhance operational sustainability. This enables informed strategic decisions, improved resource utilization, and potential alignment with ESG (Environmental, Social, Governance) standards. Practically, the findings deliver actionable recommendations for companies to overcome adoption barriers, such as investment in green technologies and navigating regulatory complexity. Environmentally, the implications are profound: adoption of green practices can reduce hazardous waste, conserve biodiversity, and minimize the carbon footprint of drug manufacturing. Economically, while initial costs for sustainable transition may be high, long-term benefits include cost savings from energy efficiency, enhanced brand reputation, and access to sustainability-driven investor capital, potentially positioning UAE pharma firms as regional leaders in green innovation.

CONTRIBUTION AND ORIGINALITY

This study makes a unique contribution by investigating the intersection of green pharmaceutical practices and environmental sustainability within the UAE, a context that remains underexplored in global research. The originality of the work lies in its dual methodological approach—using both PLS-SEM quantitative modelling (via ADANCO) and in-depth qualitative expert interviews—to validate the conceptual model. By analysing relationships between constructs such as Green Extraction Techniques, Natural Ingredient Sourcing, Green Synthesis & Formulation, and Institutional & Policy Support, the study introduces a novel framework tailored to the Middle East's regulatory and environmental landscape. It also extends the application of sustainability theories in a sector traditionally overlooked in green policy discourse. Moreover, this research fills a critical gap by offering practitioner-oriented insights for pharmaceutical firms aiming to integrate eco-conscious practices without compromising clinical efficacy or regulatory compliance.

LIMITATIONS

While the study offers strong theoretical and practical contributions, it is not without limitations. Firstly, the research design is cross-sectional, capturing respondent perceptions at a single point in time; thus, it cannot establish causal relationships. Secondly, the reliance on self-reported data may introduce bias, particularly regarding sensitive issues like environmental compliance or sustainability performance. Thirdly, while expert interviews add richness, their number (15) limits generalizability. A larger, more diverse qualitative sample might uncover additional regional nuances. Moreover, the focus on the UAE restricts the broader applicability of findings to countries with differing policy frameworks, economic constraints, or ecological conditions. Finally, due to data access limitations, quantitative metrics such as actual carbon reduction or energy savings were not captured, which may have strengthened the environmental performance validation.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future studies could expand this research by adopting a longitudinal design to evaluate how pharmaceutical companies in the UAE transition to sustainable practices over time and assess long-term environmental impact. There is also scope for comparative research across the GCC region, exploring how different countries support or regulate sustainable pharmaceutical innovation. In addition, future studies should explore consumer perspectives and willingness to pay for green medicines—an area crucial for gauging market readiness and adoption. Integrating objective sustainability metrics, such as carbon emissions, lifecycle assessments, or ESG compliance scores, would enhance the validity of outcomes. Finally, future research can explore the role of technology—such as blockchain for supply chain traceability or AI for sustainable sourcing optimization—in driving environmental sustainability in pharmaceuticals.

CONCLUSION

This study provides robust evidence for the critical role of sustainable practices in ensuring the environmental viability of the pharmaceutical industry in the UAE. The integrated findings reveal that Green Extraction Techniques and Institutional & Policy Support significantly drive environmental sustainability outcomes, while Natural Ingredient Sourcing plays an indirect yet pivotal role. The conceptual model tested via PLS-SEM using ADANCO showed strong explanatory power (R^2 = 0.747), and the qualitative interviews with domain experts validated the strategic importance of green adoption. The study thus delivers a data-driven roadmap for pharmaceutical firms, policymakers, and research institutions to transition toward eco-friendly practices. As the UAE continues its ambitious sustainability vision under the Green Agenda 2030, this research offers timely insights to align pharmaceutical innovation with environmental and economic goals, positioning the nation as a regional hub for green healthcare innovation. The findings of this study carry significant strategic consequences for the UAE's future pharmaceutical landscape, particularly as the nation advances its Vision 2031 and Green Agenda 2030. By integrating sustainable sourcing, green extraction, and eco-friendly synthesis, UAE-based pharmaceutical firms can position themselves as regional leaders in natural, ethical, and environmentally responsible medicine production. This could attract impact investors, R&D collaborations, and export opportunities in the growing global market for green wellness and plant-based remedies. For emerging markets and developing nations, the UAE's roadmap offers critical lessons on regulatory alignment, institutional support, and cross-sectoral innovation, showcasing how a desert ecosystem can leverage biodiversity, technological readiness, and government incentives to support green pharmaceutical growth. Globally, similar models are evident in India's AYUSH framework, Germany's phytopharmaceutical regulations, and China's integration of Traditional Chinese Medicine (TCM) into modern sustainability protocols. These use cases, much like the UAE's model, show that hybrid health systems combining traditional plant-based knowledge with modern environmental frameworks can promote ethical, scalable, and resilient health innovation. The UAE's focus on natural ingredient IP protection, policy-led subsidies, and AI-enhanced formulation further sets a precedent for how nations can balance innovation with environmental responsibility in medicine manufacturing. As climate change, health equity, and bioethics converge globally, the UAE's evolving green pharma ecosystem may serve as a blueprint for future-ready, sustainable healthcare economies.

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