

A Mixed-Methods Assessment of Inhaler Sustainability across the Respiratory Care Pathway

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Abstract

Inhalers are central to asthma and COPD care but contribute to the environmental impact of respiratory services. Sustainability efforts have often focused on reducing device-level carbon emissions, particularly through switching from pressurised metered-dose inhalers to lower-carbon alternatives. This study used a convergent mixed-methods design, informed by socio-technical systems theory, to examine inhaler sustainability across the UK respiratory care pathway. Interviews were conducted with patients, healthcare professionals, policymakers, industry representatives, and sustainability experts (n = 29), alongside surveys of patients on inhaler appearance and recognition (n = 65) and of healthcare professionals on disposal and recycling practices (n = 76). Findings show that inhaler sustainability is shaped by interconnected factors, including device design, regulation, prescribing systems, patient usability, and end-of-life infrastructure. Sustainability was rarely prioritised in prescribing, and recycling pathways were poorly embedded in care. Improving inhaler sustainability requires whole-system action that protects clinical safety, usability, and equitable respiratory care.

Introduction

Respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD) represent a substantial and growing global health burden, affecting hundreds of millions of individuals worldwide and accounting for significant morbidity, mortality, and healthcare utilisation^{1,2}. Inhalers remain the cornerstone of treatment for these conditions, enabling targeted drug delivery to the airways with a rapid onset of action and reduced systemic exposure. As a result, billions of inhaler devices are prescribed, used and disposed globally each year^{3,4}.

While inhalers are clinically indispensable, increasing attention has been directed toward their environmental impact. Older pressurised metered-dose inhalers (pMDIs), which rely on hydrofluoroalkane (HFA) propellants, contribute disproportionately to the carbon footprint of respiratory care due to the high global warming potential of these gases^{5,6}. In several high-income countries, inhaler use has been estimated to account for a measurable fraction of healthcare-related greenhouse gas emissions^{7,8}. Whilst this may improve with the newer generation of lower emission pMDIs⁹ and switching to dry powder inhalers (DPIs) or soft mist inhalers^{10,11}, inhaler devices are predominantly single-use or partially recyclable, leading to significant material waste and limited circularity within current supply chains^{3,12}. Furthermore, device substitution is not always clinically appropriate or feasible for all patients^{13,14}, and propellant innovation alone does not address the broader sustainability challenges associated with inhaler prescription^{15–17}, use^{18–20}, and end-of-life disposal^{21–24}, given the complexity and the interrelationship between several aspects of the inhaler lifecycle²⁵. A more comprehensive approach is therefore required, one that considers inhalers as complex systems embedded within healthcare, social, industrial, and environmental contexts.

Socio-technical systems theory (STS)²⁶ provides a useful lens of framing sustainability as an emergent property of interactions between people (patients, primary care clinicians, pharmacists, waste services, industry and policymakers), technologies (devices, materials and packaging), organisational routines and wider regulatory and infrastructural contexts (Fig. 1). In this view, behaviours that appear ‘individual’, such as advising on disposal, discarding inhalers in clinical waste, are shaped by prescribing systems, workflow pressures, local service arrangements, and the healthcare access. Taking an STS approach to the inhaler lifecycle perspective could therefore be informative in identifying leverage points for change and anticipating the unintended consequences of interventions that focus solely on one stage of care.

Existing work has largely focused on carbon footprint estimates of different inhaler classes^{5,19,27} and on modelling the impact of switching from high- to lower-carbon devices^{10,11,13}. Despite growing policy and clinical guidance supporting low-carbon inhaler prescribing and sustainability^{28,29}, there remains limited empirical evidence on how sustainable inhaler care is implemented in routine primary care, where most inhalers are prescribed, reviewed and changed. In particular, it is unclear how sustainability is prioritised alongside clinical considerations in prescribing, how device features that support safe use, (including colour and labelling) intersect with sustainability, and how local infrastructure and role boundaries between several domains of healthcare shape what is feasible for inhaler return, disposal and recycling.

This study aims to identify key barriers, trade-offs and opportunities to improve inhaler sustainability in primary care.

Methods

Study design

We conducted a convergent mixed-methods study to examine sustainability across the inhaler lifecycle. Qualitative interviews and two quantitative surveys were conducted in parallel, analysed separately, and integrated during interpretation.

Study Setting

The study was conducted in the United Kingdom between August 2024 and January 2025, where inhaler prescribing and long-term management of asthma and COPD occur predominantly in primary care.

Participant sampling and recruitment

Quantitative and qualitative components used complementary, non-probability sampling appropriate to the exploratory, systems-focused aims of the study. For the surveys, we used convenience sampling to recruit healthcare professionals and inhaler users across the UK via professional networks, patient charities and social media. Qualitative interviews used purposive sampling, supplemented by snowball recruitment, to capture diverse stakeholder

perspectives across the inhaler lifecycle. Together, these approaches enabled inclusion of participants positioned at different stages of inhaler prescribing, use, disposal and end-of-life management. All participants provided informed consent.

Data collection

Qualitative interviews

Semi-structured interviews explored stakeholder experiences and perspectives on inhaler sustainability across the inhaler lifecycle, including inhaler design, inhaler choice and prescribing, patient education and use, repeat prescribing and dispensing behaviours, sustainability considerations, disposal and end-of-life pathways. Interviews were conducted online, audio-recorded, transcribed verbatim, and anonymised. Interviews lasted 30-60 minutes.

Quantitative surveys

Two cross-sectional surveys (see supplementary material), distributed electronically and completed anonymously, were conducted to complement the qualitative findings:

Survey 1: Patient perspectives on inhaler use.

A survey exploring perceptions was administered to patients prescribed inhalers. The survey examined how device appearance influences inhaler recognition, use, and potential implications for sustainability-related device changes.

Survey 2: Healthcare professional perspectives on the inhaler disposal.

A survey examining knowledge, attitudes, and behaviours was administered to healthcare professionals (HCPs) working in primary and secondary care. Items addressed disposal pathways, awareness of environmental impacts, and perceived barriers to sustainable disposal behaviour.

Data analysis

Qualitative analysis

Interview transcripts were coded using Nvivo version 14 and analysed using reflexive thematic analysis, following Braun and Clarke's approach³⁰. Coding was iterative and abductive. Coding and theme development were conducted by one researcher (OA), trained in qualitative research, with regular analytic discussions with another researcher (IA) to refine interpretations and map themes across stages of the inhaler lifecycle.

Quantitative analysis

Survey data were analysed using SPSS version 29 for descriptive statistics to summarise participant characteristics and response patterns.

Mixed methods integration

A mixed methods integration occurred at the interpretation stage through triangulation of qualitative and quantitative findings. Findings were compared across methods and stakeholder groups to identify convergence, divergence, and complementarities, enabling identification of system-level barriers, trade-offs, and leverage points for improving inhaler sustainability.

Ethics

Ethical approval was obtained from the University of Birmingham ethics committee with approval number RG_23-068. Written informed consent was obtained from all participants prior to enrolment in the study, in accordance with the principles of the Declaration of Helsinki.

The datasets generated and/or analysed during the current study are not publicly available because they contain qualitative interview data that potentially identify participants, given the involvement of specialist stakeholder groups. De-identified data may be made available from the corresponding author on reasonable request, subject to institutional data governance requirements.

Results

Overview of Findings

Twenty-nine stakeholders across the inhaler lifecycle participated in qualitative interviews (Figure 2). Two surveys were conducted to complement interview findings: patients (n = 65) and HCPs (n = 76).

Across qualitative and quantitative data, inhaler sustainability emerged as a system-level challenge shaped by interactions across the inhaler lifecycle rather than by individual behaviour alone (Figure 3). Stakeholders consistently described tensions between environmental sustainability goals and established priorities relating to clinical safety, usability, and service delivery. Results are organised around key stages of the inhaler lifecycle, including upstream design and regulation, prescribing and system constraints, human factors and inhaler use, and end-of-life disposal and recycling.

1. Upstream design and regulatory decisions shape sustainability options downstream

Stakeholders described inhaler sustainability as strongly influenced by upstream design, manufacturing, and regulatory decisions, which set practical limits on what can be achieved in clinical settings. As one respondent noted,

We're a heavily regulated industry; any change we make can take a long time and requires multiple country approvals. Typically, a significant change to a pharmaceutical product would take somewhere between three and five years to be fully completed globally. (Pharmaceutical 13a)

Industry, academic, and policy participants emphasised that inhalers are highly regulated combination products, meaning that changes to materials, propellants, or design features require extensive testing and regulatory approval. As a result, sustainability-related modifications were often described as slow to implement and constrained by safety and regulatory requirements.

But for an existing product, if we're changing the excipients or having a new valve, you're talking between around seven years. If you're really lucky between five and seven years. (Pharmaceutical 16)

These upstream constraints were repeatedly linked to downstream implications for prescribing and use. Several stakeholders highlighted that features such as inhaler size, form, and colour are not simply aesthetic, but can influence patient recognition, training, and safe use. Inhaler colour in particular, was described as a design feature that carries implicit meaning in clinical practice and patient education, despite not being formally standardised.

Sometimes if I'm talking to a patient, I have to get a picture up on my computer to make sure we know we have a shared understanding of which inhaler we're talking about. I think patients often find it difficult to describe what their inhaler looks like because it is difficult to describe what an inhaler looks like and to describe the difference between one inhaler and another except by colour (GP 012)

I think inhalers need to be colour coded for obvious clinical reasons in terms of patients being able to identify what is a salbutamol, a short acting inhaler, a long acting inhaler. I think that's important. (Academia 001)

2. Clinical and system pressures shape prescribing decisions

Healthcare professionals consistently described inhaler prescribing as guided primarily by clinical effectiveness, patient capability, guideline alignment, and formulary restrictions. While many clinicians expressed support for improving the environmental sustainability of inhaler use, sustainability considerations were typically secondary to immediate clinical priorities and were shaped by system-level factors such as electronic prescribing systems' default inhaler listing, local formularies, and medicines-optimisation policies.

I think the other challenge we have is with electronic prescribing. You're getting new type of prescribing errors. So you end up selecting off a list. So we see a lot in our organisation where people will probably selecting from the top of the list, which is often an MDI rather than a dry powder version (Pharmacist 028)

If you look at the dry powder inhalers, they tend to be more expensive than metered dose. There are metered dose inhalers with a lower global warming potential, but it isn't 0. And again, when people are looking at the money, they'll go to the cheapest option at the moment, 'cause. We've got to save it. (Regional Pharmacist, 004)

Participants reported that sustainability-driven device changes often require additional time for patient explanation, inhaler technique training, and follow-up, which can be difficult to accommodate within routine consultations. As a result, clinicians described a tension between aspirations to reduce environmental impact and the practicalities of delivering safe, effective care.

Shared decision-making was viewed as important but challenging, particularly for patients with long-established inhaler routines or those using multiple devices. Several stakeholders noted that changes introduced without adequate support risk undermining patient confidence, adherence, or technique.

Anytime you allow for a greater level of Clinician discretion, you add to the workload because an additional choice being made is time and ...a 10-minute appointment very quickly becomes 20 minutes. I'm sure there are a lot of doctors when they're busy that there are some days when you might sign 100 prescriptions, and you don't necessarily have time to go through each one and think-right which of these were the best inhalers? (Healthcare advocacy lead 011)

3. Human factors and usability constraints shape inhaler use

Across interviews and survey data, human factors emerged as central to how patients use inhalers and how they respond to sustainability-related changes. Clinicians described established routines, device familiarity, and quick-recognition cues, notably colour as integral to patient confidence, adherence, and technique, particularly for patients using multiple devices or managing exacerbations. Patients likewise reported relying on visual cues to support rapid identification and correct use in everyday contexts.

I think there's less comfort for the patients changing devices and changing ingredients at the same time. That means that they feel like 'this is a completely new device. I have no idea how to use it, and it's got different ingredients, it's different colour', it feels very alien to them. (Respiratory doctor 010)

I've probably had six different designs of {redacted} inhalers in about 15 years, and that feels unnecessary at this point. It's not a new medication. So why does it keep changing? (Patient 026)

These qualitative insights were reflected in the patient survey ($n = 65$), which demonstrated substantial heterogeneity in how inhaler colour is perceived and used. 34% of respondents reported that they almost always used colour to differentiate (Figure 4a). This reliance on colour was not evenly distributed across patient groups (Figure 4b). Among those with COPD, 59% reported that colour affected the consistency of their inhaler use, compared with 29% of patients with asthma ($\chi^2 = 4.46$, $p = 0.035$). A similar pattern was observed for socioeconomic factors with 56% of respondents with a household income below

£30,000 relying on colour, compared with 44% who did not ($\chi^2 = 6.38$, $p = 0.012$). This threshold was below the UK median household disposable income around the survey period (£36,700 in FYE 2024)³¹, indicating greater colour reliance among lower-income respondents.

Further analysis (Figure 4c) highlighted the functional role of inhaler colour in patient decision-making and communication, particularly for distinguishing between devices. These findings show that colour serves as a meaningful cue for certain patient subgroups, indicating that sustainability-driven changes may have differential, and potentially inequitable, effects on safe inhaler use.

4. Inhaler Disposal and recycling remain weakly integrated into routine care

Across interviews, stakeholders identified disposal and recycling as the least embedded stage of the inhaler lifecycle, with limited integration into patient education, prescribing reviews, or follow-up.

I think most patients don't just don't realise that's what they should be doing and I don't think anyone's ever told them before. When I've told patients that they should be taking them back to pharmacy, they're often quite surprised and they're quite happy to do it. And they understand. When I explain to them the reasons. (Doctor 029)

Disposal was commonly characterised as an adjunct activity dependent on local initiatives, and participants described persistent uncertainty about where responsibility sits across general practice, community pharmacy, and waste services. As one participant noted, *Having sort of drop off points at primary or secondary care is also useful because those patients do tend to attempt to appointments or do tend to go to their GP quite a lot. You can see their GP for exacerbations picking up prescriptions at pharmacies in the community. So I think there needs to be multiple different processes and pathways for patients to be able to recycle the inhalers (GP 012).*

Survey findings reinforced this implementation gap. Among healthcare professionals ($n = 76$), awareness of appropriate inhaler disposal or recycling was high (85.5%), yet only 12.5% reported a formal disposal or recycling scheme in their setting, indicating that awareness does not translate into routine practice in the absence of provision. Where inhaler recycling schemes existed ($n = 8$), respondents reported high familiarity with processes but low patient engagement, limited staff capability, and low satisfaction with current practice. These challenges were echoed in interviews and were often attributed to a lack of resources or infrastructure, as a respondent noted *'The challenge has always been: what do you do with the returned inhalers? How do you encourage people to bring them back? And once you have them, what do you do with them? (Sustainability expert 006).*

Among respondents without a scheme ($n = 56$), barriers were predominantly structural, with funding and infrastructure constraints most frequently cited, followed by lack of policy support, competing service demands, and absence of incentives; patient disinterest was infrequently endorsed as a primary barrier (Figure 5a). Further analysis showed differential constraints by setting and role, with primary care respondents more likely to identify inadequate infrastructure and lack of incentives as barriers, and doctors more likely than other professionals to identify the absence of government policy as limiting (Figure 5b).

Overall, these findings suggest that limitations in inhaler disposal are driven less by motivation than by misalignment with service design, governance, and waste infrastructure. Without clear ownership, sustained resourcing, and consistent end-to-end pathways, disposal and recycling programs are unlikely to be implemented at scale or maintained over time.

Discussion

Our findings validate the importance of social and technical factors in shaping inhaler sustainability in practice. Inhaler sustainability emerged as a socio-technical systems challenge, with device design, regulation, prescribing practices, patient use, and end-of-life infrastructure all influencing what is feasible. Sustainability was therefore continually balanced against clinical safety, usability, and service delivery priorities, helping to explain why isolated interventions are unlikely to achieve sustained impact.

Manufacturing and regulation were identified as upstream determinants of inhaler sustainability. As highly regulated medical devices, changes to inhaler materials, propellants, components, or dose-delivery mechanisms require robust evaluation to ensure safety and efficacy. This creates an inherent tension between innovation, environmental sustainability and regulatory assurance, shaping the pace and form of lower-carbon or more recyclable device development^{32,33}. Participants also noted that features such as device structure and colour have practical implications for recognition, training, and safe use^{34,35}. Sustainability is therefore partly determined early in the product lifecycle, suggesting that environmental, usability, affordability, and end-of-life considerations should be incorporated into design and regulatory processes rather than addressed primarily through downstream interventions.

Prescribing represented a key point where environmental goals intersected with clinical, organisational, and financial constraints. Although clinicians supported lower-carbon inhaler options in principle, decisions were shaped by formularies, guideline requirements, electronic prescribing systems, cost pressures, and limited consultation time. Sustainability was therefore weighed against symptom control, patient capability, medication safety, and service workload, consistent with evidence that prescribing behaviour is shaped by system-level determinants as well as individual preference^{36,37}.

The cost implications of switching inhalers also require nuance, particularly for combination inhaled corticosteroid/long-acting β_2 -agonist (ICS/LABA) inhalers, where both pMDI and DPI options may be available. Although switching from pMDIs to DPIs can substantially reduce greenhouse gas emissions¹⁰, the financial impact depends on the specific device, brand, and formulary comparator. For instance, current UK pricing indicates that some branded beclometasone/formoterol pMDI and DPI products are similarly priced, whereas lower-cost beclometasone/formoterol pMDI alternatives may remain substantially cheaper than corresponding branded DPI options³⁸. Affordability is therefore not simply a trade-off between pMDI-DPI, but reflects broader

issues including brand availability, formulary positioning, and access to lower-cost alternatives. Without aligned formularies, prescribing-system prompts, and time for patient review and inhaler technique support, lower-carbon inhaler switching may be difficult to implement safely and equitably at scale.

Switching patients to alternative devices was perceived as requiring additional time for explanation, training, and follow-up, resources that are often scarce in primary care consultations. Evidence from research indicates that switching from pMDIs to DPIs can reduce greenhouse gas emissions substantially¹⁰, but comes at a cost.³⁹. Our findings suggest that, without system-level support, such transitions may be difficult to implement safely at scale.

Human factors emerged as central at the inhaler point of use. Patients and clinicians described familiarity, habit, sensory properties, and visual cues, including colour, as supporting safe and confident inhaler use. Survey findings indicated greater reliance on colour among patients with COPD and those from lower-income households, suggesting a potential equity risk if sustainability-driven design changes reduce recognisability or disrupt established routines. Patients prioritised safety, usability, and symptom control over environmental considerations, indicating that reluctance may reflect concerns about medication error or loss of confidence rather than opposition to sustainability. Interventions perceived to compromise familiarity or symptom control may therefore reduce engagement unless accompanied by explanation, reassurance, shared decision-making, and follow-up support, particularly for older patients and those using multiple inhalers⁴⁰.

Inhaler end-of-life disposal and recycling appeared least embedded within routine care. Although healthcare professionals were aware of disposal challenges, formal recycling schemes were uncommon, inconsistently available, and poorly integrated. Barriers were mainly structural, including limited infrastructure, unclear ownership, lack of incentives, and insufficient policy support. Manufacturer, brand, or pilot-specific inhaler recycling schemes may also be difficult for patients using multiple inhaler products, limiting their value as a consistent system-wide pathway. These findings align with evidence that effective recycling requires coordinated governance, sustained funding, and integration into routine services rather than reliance on short-term pilots^{24,41}. This is particularly relevant in primary care, where workload pressures limit the feasibility of additional sustainability tasks without dedicated infrastructure.

Overall, the findings show that inhaler sustainability is produced through interactions across the respiratory care pathway. Device design, regulation, prescribing systems, patient behaviour, clinical workload, affordability, and waste infrastructure collectively shape what is feasible in practice. Single-stage interventions, such as promoting DPIs, redesigning devices, or establishing recycling schemes, are therefore unlikely to produce meaningful or equitable change without wider system support. A lifecycle-oriented approach is needed, embedding environmental considerations into innovation and regulation, aligning prescribing systems, protecting patient safety and usability, addressing affordability, and developing reliable end-of-life infrastructure. Such an approach should avoid shifting responsibility onto patients or frontline clinicians without the structural support required to make sustainable inhaler use feasible.

Future research should evaluate how inhaler sustainability interventions operate in routine care, including their effects on adherence, medication safety, patient confidence, clinician workload, cost, and health equity. Comparative studies across healthcare systems may help distinguish transferable solutions from those dependent on local prescribing, regulatory, or waste-management contexts.

Strengths and limitations

This study benefits from the integration of qualitative and quantitative data across multiple stakeholder groups and stages of the inhaler lifecycle, providing a comprehensive view of inhaler sustainability as a socio-technical system. However, several limitations should be acknowledged. The study was conducted in the UK, which may limit generalisability to other healthcare systems. Survey samples were modest, and some subgroup analyses were limited by missing data. In addition, self-reported behaviour may not fully reflect actual behaviour, particularly in relation to inhaler disposal. Finally, findings should also be interpreted in relation to the timing of data collection, as UK respiratory guidance and NHS sustainability policies have continued to evolve, including updated asthma recommendations published in November 2024 and ongoing NHS net-zero commitments for medicines and inhaler prescribing.

Conclusion

Inhaler sustainability cannot be achieved through isolated changes to devices, prescribing, or disposal alone. Our findings show that sustainability outcomes are shaped by interdependencies across the inhaler lifecycle, including device design and regulation, prescribing systems, patient use, affordability, and end-of-life infrastructure. Addressing the environmental impact of inhalers therefore requires coordinated approaches that embed sustainability into routine respiratory care while preserving clinical safety, usability, and equity. Such approaches may include formulary alignment, prescribing decision support, shared decision-making, inhaler technique review, feedback on prescribing-related carbon impact, and accessible inhaler return or disposal pathways. Bringing these components together is likely to be more effective than relying on single interventions or shifting responsibility onto patients and clinicians without adequate system support.

Declarations

Author contributions

AO undertook tool development, with support from KM, AI, and AT. AO conducted the interviews, survey analysis, qualitative analysis, and drafted the first version of the manuscript. AI supported the qualitative analysis and interpretation of findings. AT contributed to the overall conception, ideation, and governance of the work. All authors read and approved the final version of the manuscript.

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Competing interests

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Figures

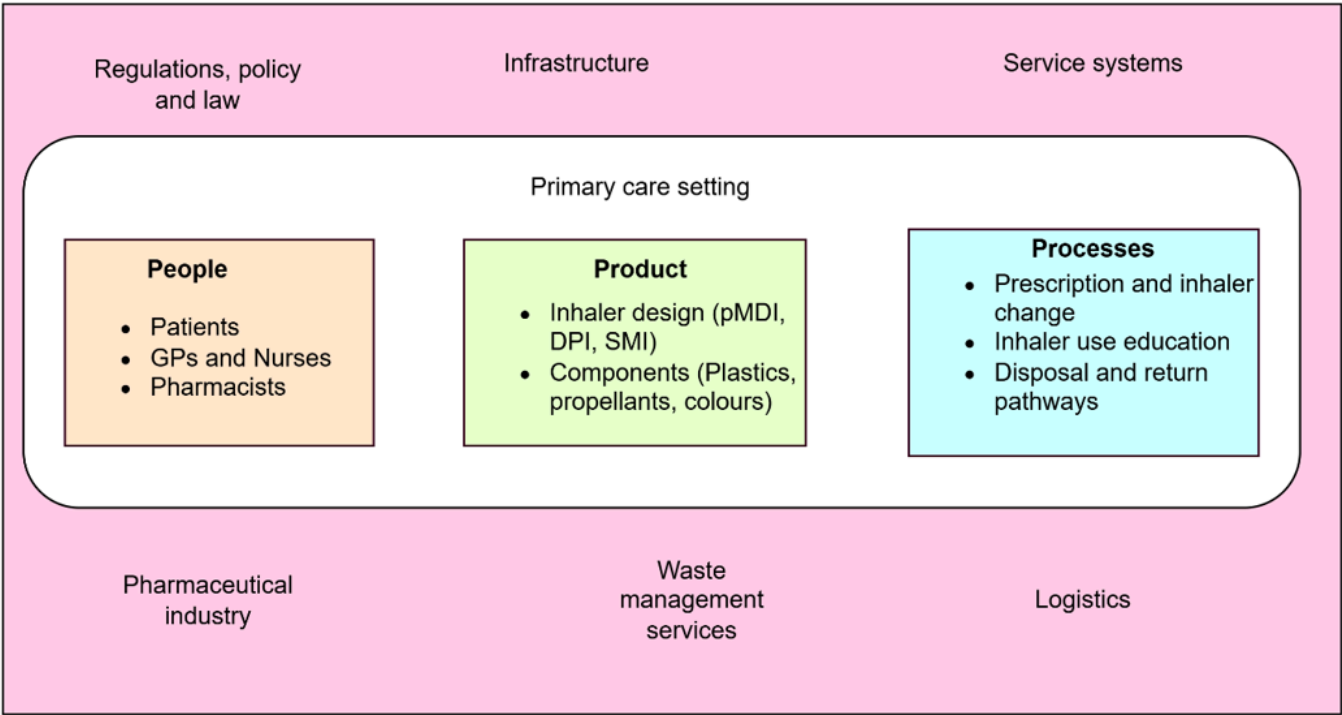


Figure 1

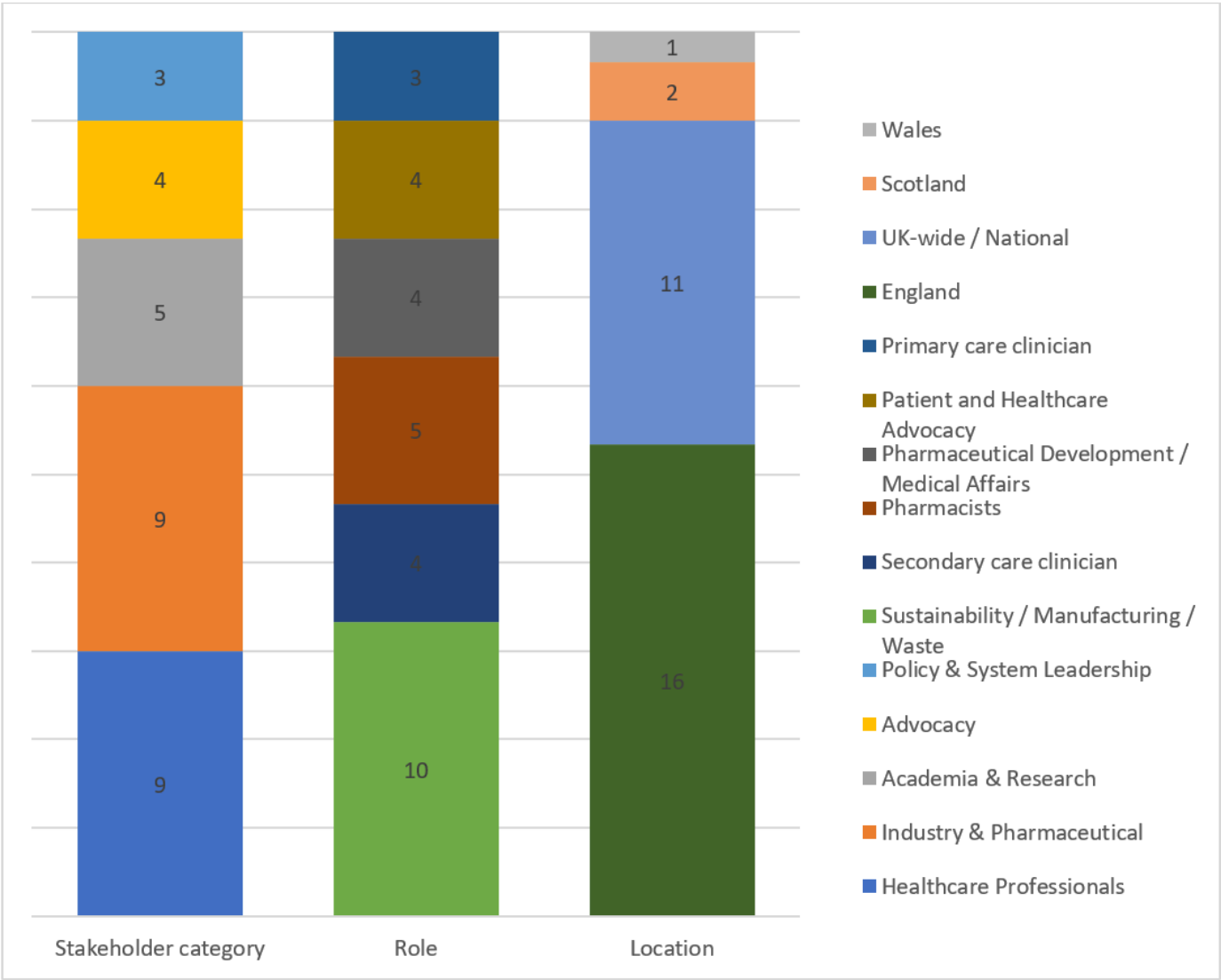


Figure 2
Qualitative interview Stakeholder categories.

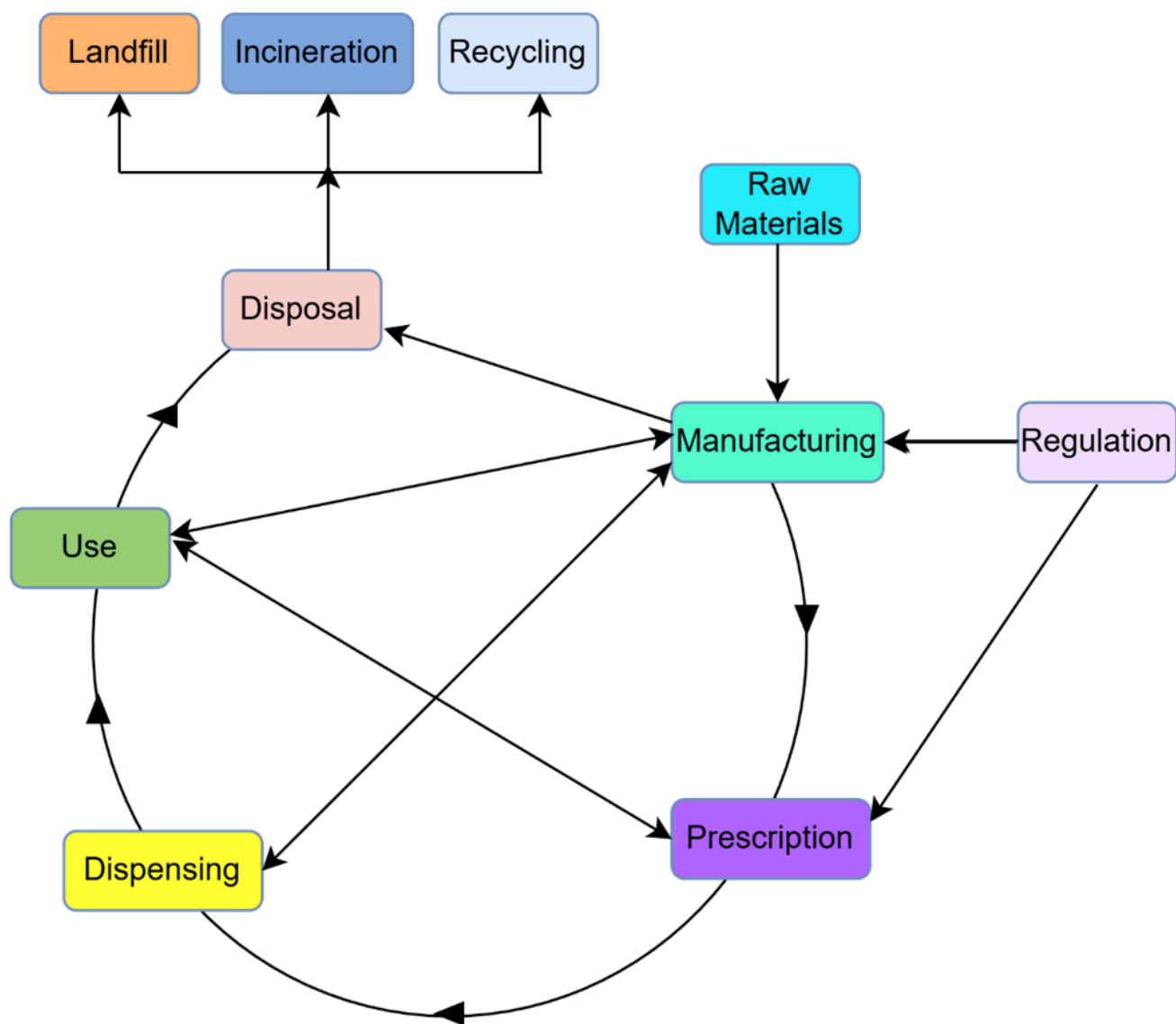


Figure 3
Interdependencies across the inhaler lifecycle.

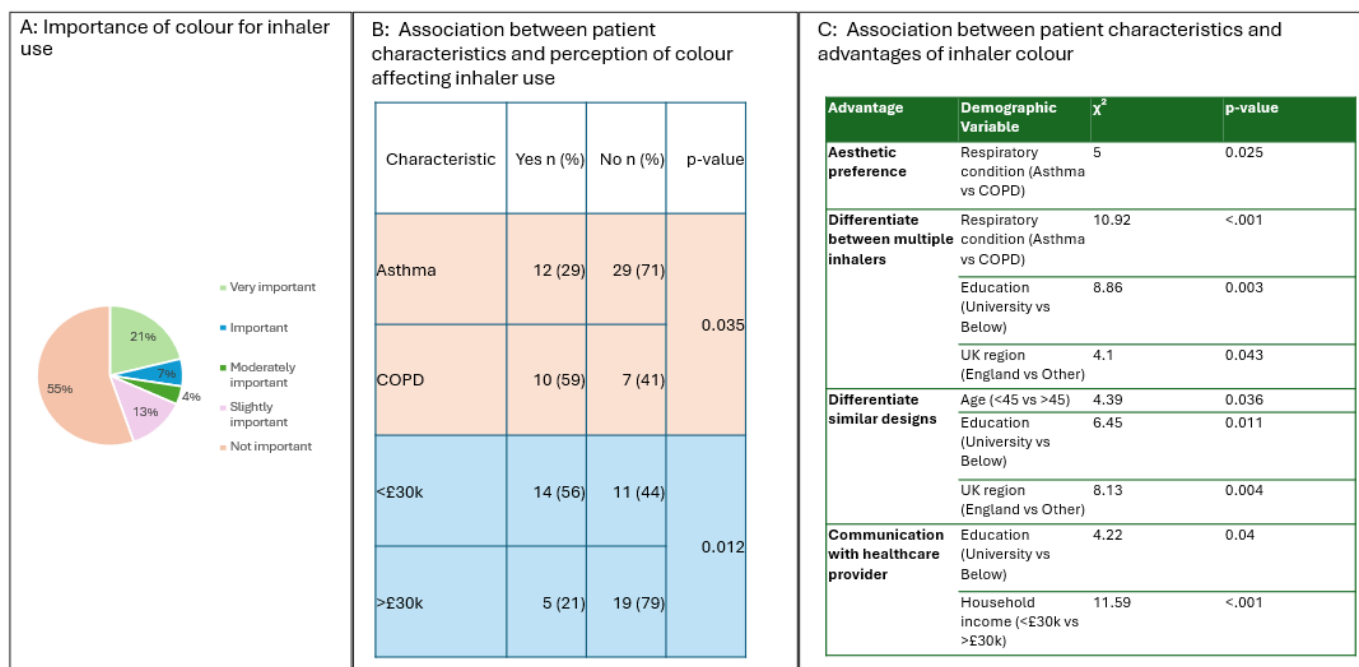


Figure 4

Human factors in inhaler use and sustainability.

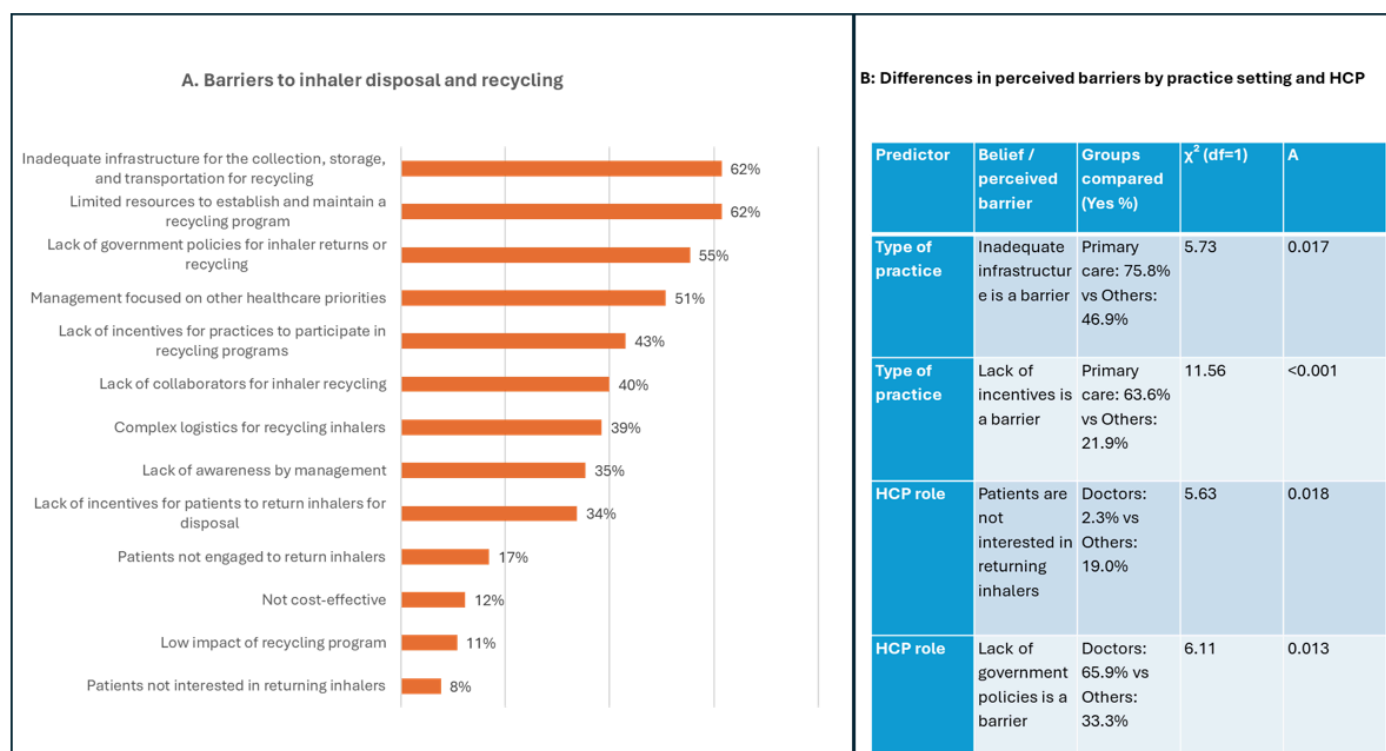


Figure 5

Barriers to inhaler disposal and recycling

Supplementary Files

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- [Supplementaryfile1surveyquestionnaires.docx](#)