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Research article

Moving waste storage towards a circular economy: barriers and opportunities

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ABSTRACT

Many countries have policies to transition to a circular economy, yet wastes continue to be landfilled despite often containing valuable resources. Conventional landfills are unsustainable and many countries have adopted targets to reduce the amount of waste being deposited in them. This paper explores the barriers and opportunities of a novel approach to landfill design: the 'ASPIRE waste repository concept' where ore-forming processes are engineered in, so that the valuable components of waste can be recovered. To do so, we draw on a literature review and in-depth, semi-structured interviews with twenty stakeholders from the waste management, engineering and environmental management sectors. We found that there are significant opportunities for the ASPIRE concept, particularly in current policy towards a circular economy and the liabilities associated with the long-term storage of waste in landfills. However, the analysis highlighted several interwoven barriers that need to be overcome, including the need to shift the economic conditions and regulatory framework to enable the technology, and demonstrate the environmental performance of the repositories and the long-term efficacy of the resource recovery. If these could be addressed, this ASPIRE concept could provide a practicable circular economy solution for materials that would otherwise go to conventional landfill.

1. Introduction

We are faced with significant global challenges related to the supply of, and access to, aggregates and critical materials. At the same time, industrial, mining and mineral activities generate vast quantities of wastes. These waste streams can be broadly categorised into industrial waste, mineral waste and dredging spoil. It is estimated that the UK produced 12.4 million tonnes of industrial waste in 2020 (Defra, 2023a), 47.4 million tonnes of mineral waste in 2021 (Mitchell et al., 2023), and 11.3 million tonnes of dredging spoil in 2018 (Defra, 2023b). Across Europe, mining and quarrying activities in the EU-27 generated 598.9 million tonnes of waste in 2018 (Eurostat, 2020), and dredging activities 77.5 million tonnes of waste (Eurostat, n.d.). Added to this we have significant quantities of legacy waste produced from historical industrial activities, which are often found near their point of production, with 30, 281 legacy waste sites identified in England and Wales (Riley et al., 2022).

Whilst there is a shift towards embracing the circular economy concept, despite the vast quantities of mineral wastes produced, they often do not appear prominently in discussions around the circular economy. Currently, landfills or other engineered impoundments are key disposal methods for these materials, despite containing valuable resources such as critical metals (Crane et al., 2017), soil macronutrients, and mineral constituents that contribute to the sequestration of atmospheric CO_2. Although there are markets for some of these waste materials, for many the concentration of valuable resources is too low, and concerns over quality and legislation focused on waste management act as barriers to more widespread use.

One potential solution is landfill mining, which excavates waste from landfills for external processing. However, a more innovative approach termed ASPIRE (Accelerated Supergene Process in Repository Engineering), proposes to transform waste repositories into active sites for resource recovery and environmental remediation (Sapsford et al., 2023 offers detail on the theoretical grounding of the ASPIRE concept). The ASPIRE concept uses naturally occurring plant-derived chemical solutions known as lixiviants, which help dissolve and mobilise metals from waste materials. A lixiviant is an aqueous solution used in hydrometallurgy to selectively extract metal ions from ores or concentrates by

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dissolving them into solution (Wang, 2007). This, combined with biogeochemical reactions, accelerates ore formation within waste repositories. The result is termed an "anthropogenic ore", where waste products or materials created by human activity from industrial operations have led to a sufficient accumulation of metals that their extraction becomes economically viable (Seetharam and Jung, 2016). This enables valuable metal resources to be recovered and decontaminates the waste, thus providing a potential material that can be used as a secondary aggregate (Sapsford et al., 2023).

Importantly, the ASPIRE concept aims to complement rather than displace existing economically viable and sustainable recycling technologies for mineral-rich wastes. Instead, it advocates an approach for the temporary storage of waste in these repositories, whilst at the same time treating the stored materials to enable the recovery of valuable materials and decontaminated aggregate. Nonetheless, there are various significant engineering and policy challenges, including alignment of the process with current waste and planning regulations, economic feasibility of the process, and uncertainty concerning any impact on the environment, health and safety compared with an engineered landfill system.

The ASPIRE concept represents a transdisciplinary innovation, drawing on insights from materials science, microbial ecology and bioremediation, and climate and biodiversity policies. From materials science, it relies on the ability of lixiviants and biofilms to selectively capture and bind metals, with factors like ion exchange and surface chemistry playing a key role in how effectively metals can be recovered (Wang, 2007; Ferris et al., 2000). At the same time, ASPIRE benefits from understanding microbial communities: bioleaching consortia work together through complex metabolic processes that speed up metal mobilization and the formation of new mineral deposits in waste materials (Johnson, 2014; Baker and Banfield, 2003). Finally, ASPIRE's environmental significance is clear when viewed through the lens of climate and biodiversity policies; it helps prevent greenhouse gas emissions by reducing the energy-intensive processes needed for traditional mining, supporting circular economy goals and efforts to lower carbon footprints (Cucchiella et al., 2015; Kirchherr et al., 2017). This also reduces habitat destruction and the greening of ASPIRE repositories contributes to nature restoration objectives (Burlakovs et al., 2017). By combining these different fields, ASPIRE offers a powerful approach to recovering valuable metals while also addressing environmental challenges.

This paper draws on a review of literature and stakeholder interviews to present the factors that may act as barriers or opportunities in the drive to moving waste storage towards a circular economy model. It seeks to answer the questions: what are the factors that are likely to act as a barrier to the adoption of the ASPIRE concept in the management of industrial, mining and mineral wastes? And what opportunities exist to facilitate the adoption of the ASPIRE concept? Although, other studies have explored barriers and enablers towards more sustainable resource use, for example in construction (e.g. Ajayi and Oyedele, 2017; Dewick et al., 2019) and mining (e.g. Tayebi-Khorami et al., 2019; Janikowska and Kulczycka, 2021), the ASPIRE concept has not been explored before having been first introduced in Sapsford et al. (2023). The approach used in this paper to understand the factors that may act as barriers or opportunities to the ASPIRE concept is a PESTLE (political, economic, social, technological, legal and environmental) analysis. By assessing each of these factors based on the review of literature and stakeholder interviews, the paper aims to identify opportunities, anticipate threats and suggest strategies to mitigate these identified barriers. Despite focusing on the ASPIRE concept, the factors that are explored are likely to have salience with other emerging technologies that aim to move towards a circular economy.

2. Methods

2.1. PESTLE analysis

PESTLE is a macro-environmental analysis tool used to explore factors that may influence strategic business decisions (Song et al., 2017), including those concerning a future market, organisation or industry (Dalirazar and Sabzi, 2020). PESTLE has also been widely applied in studies exploring sustainable technologies, including waste management, to assess the barriers, opportunities and risk associated with their adoption (Song et al., 2017; Dalirazar and Sabzi, 2020; Loy et al., 2023). The factors are categorised into six domains: political, economic, social, technological, legal and environmental. Here we conduct a PESTLE analysis of the literature and interviews with stakeholders to explore the barriers and opportunities of moving towards a circular economy model for the storage of industrial, mining and mineral wastes using the ASPIRE concept. As the ASPIRE concept is a new approach towards resource recovery, a PESTLE analysis enables a comprehensive exploration of how each of these factors may influence the adoption of the technology. Political factors consider high level government strategies and the global political context related to resource security, sustainable waste management and extractive industries. Often these are linked to economic factors, which are then explored explicitly and include financial viability, commodity prices and the costs associated with a new technology. Social factors consider the potential public perception and industry acceptance of the ASPIRE concept in terms of both the repositories themselves and the resulting resources. Similarly, the technological factors concerns the operation of the ASPIRE repositories and the properties of the resources, whilst the legal factors consider regulatory frameworks and liability concerns that may influence the adoption of the ASPIRE concept. Finally, environmental factors include impacts such as emissions and land use implications. This structured approach ensures a comprehensive evaluation of the ASPIRE concept within the broader waste management and resource recovery landscape.

The PESTLE was informed by a literature review and stakeholder interviews. As the ASPIRE concept is not currently in use, the literature related to sustainable mining and waste management, resource recovery, adopting a circular approach to waste management and landfill mining were used to infer barriers and opportunities relevant to the proposed technology. These were then used to inform the design of the interview questions, for example, with prompts on the likely public acceptability or changes to regulations that may be required.

2.2. Literature review

We followed a narrative literature review approach, with a comprehensive search strategy, followed by title and abstract screening, full-text screening and a thematic analysis (see below, Braun and Clarke, 2006). The search strategy combined three sets of terms relating to the wastes of interest (e.g. industrial waste, mineral waste, dredgings), their management and impacts (e.g. resource recovery, landfill, pollution, restoration) and the policy landscape (e.g. circular economy, regulation). Searches were carried out in Google Scholar and Scopus to identify papers and reports published from 2010 to 2023. A start date of 2010 was used as this is when the concept of circular economy gained prominence (Patwa et al., 2021) and coincides with the introduction of The Waste (England and Wales) Regulations 2011, which set out the expectations to adopting the waste hierarchy. Reference lists of selected publications were also searched for additional studies.

Publications were selected for full text screening if their titles and abstracts met the following inclusion criteria: they reported on the political, economic, social, technological, legal or environmental barriers or opportunities to adopting a more sustainable approach to industrial, mineral or dredging waste management via disposal to land. Studies were excluded if they reported on wastes not classified as industrial, mineral or dredging wastes (e.g. household, municipal solid waste), practices to reduce waste (e.g. product design, designing for deconstruction), technological design in waste management facilities (e.g. incinerators, landfills), modelling, laboratory or field-based studies focused on waste characterisation or risk assessment. Academic and grey literature were included in the review. Grey literature, in this context, refers to non-peer-reviewed sources such as government policy documents, industry reports and conference proceedings, which provide insights into real-world applications and regulatory perspectives.

Publications were added to NVivo ready for analysis (see section 2.4).

2.3. Participant recruitment

The PESTLE was further informed by interviews with stakeholders, who were asked specifically for their insights into the barriers and opportunities of moving industrial, mining and mineral waste management towards the ASPIRE concept.

Participants were recruited using several methods. First, stakeholders who had indicated an interest in the ASPIRE approach, for example, via letters of support for the research or attendance at events, were invited to participate and/or forward the invitation to other relevant stakeholders. Additional participants were identified from the personal contacts of the wider research team, online searches on LinkedIn, Google, authorship of trade publications and the speakers at industry-focused conferences. We prioritised inviting potential participants in geographical locations or with expertise in specific wastes that were under-represented in the sample.

The following criteria were used when selecting potential interviewees: knowledge of industrial, minerals or mining waste management; knowledge of recent changes in legislation and policy, UK or international; knowledge of landfill/contaminated land management. Each potential participant was invited to take part in the study via an email, which included a brief background of the ASPIRE concept, aims and objectives of the interview and details on how the interview would be conducted. The email included a Participant Information Sheet and Consent form.

The interview was designed as semi-structured and the schedule included open-ended questions allowing participants to provide answers in their own terms (Groves et al., 2004). The interviews were conducted online via Microsoft Teams; were audio recorded and digitally transcribed by the Teams transcription tool. Transcripts were checked for inaccuracies and corrected.

Ethical approval was granted by the University of the West of England Faculty of Environment and Technology Research Ethics Committee (reference: FET-2122-39).

2.4. Data analysis

Literature and interview data were analysed in NVivo using the process of thematic analysis (Braun and Clarke, 2006). Texts and interview transcripts were read, and deductive and inductive coding were used iteratively to categorise the data. Deductive codes were drawn from the terms used in the PESTLE model described above, whereas inductive codes were generated by searching for themes that captured patterned meaning across the data. The codes were then refined and accumulated into themes that represented the semantic meaning across the dataset. The results of both the literature review and interviews were then summarised based on these themes, within the structure provided by the PESTLE analysis. Secondary analysis was performed with review by other researchers to ensure the themes adequately represented the original data.

2.5. Profile of participants

In total 59 stakeholders were invited to take part in the interviews and 20 accepted (34 % response rate). A variety of disciplines and roles were interviewed (Fig. 1).

ASPIRE is a UK-based project and our sample reflected that: 80 % (n = 16) of interviewees were based in the UK, whilst 10 % were based in the European Union (n = 2) and a further 10 % were in Asia (n = 2).

3. Results and discussion

The key barriers and opportunities identified from the literature and interviews, organised into political, economic, social, technological, legal and environmental factors are shown in Fig. 2. The following sections provide a detailed discussion of each of these in turn, supported by quotes from participants. There are barriers and opportunities to the ASPIRE concept that apply to conventional technologies so the focus here is on those which may be distinct to the ASPIRE concept.

3.1. Political factors

Several political opportunities for the ASPIRE concept were identified. The first of these relates to the increasing focus by international organisations, including the European Commission, on resource security, sustainable waste management and reuse of secondary materials (Buijs and Sievers, 2011; Hill, 2015; Bartekova and Kemp, 2016; Silva et al., 2016; Burlakovs et al., 2017; Bide et al., 2020; Carvalho et al., 2021). Concerns regarding resource security and the environmental consequences of wastes have also been translated into national policies, for example in China, Japan, European Union and the UK (Silva et al., 2016; Velenturf et al., 2018) providing an opportunity for ASPIRE to contribute to their delivery. In England, The Waste (Circular Economy) (Amendment) Regulations, 2020 includes waste prevention measures to reduce industrial and mining wastes alongside economic incentives to support ‘advanced recycling’ and innovation in waste management. The European Commission’s Circular Economy Action Plan (European Commission, 2020) includes measures to ‘increase confidence in secondary raw materials’, for example, by enabling technologies that remove contaminants from waste, and ensuring there is a market for these materials. As one participant explained:

> *We see a circular economy as a contributing strongly towards the prosperous Wales, not just creating good jobs, resilient jobs, but also tackling resource efficiency and low carbon which is a key part of a prosperous Wales* (AS07).

Participants, therefore, felt that the ASPIRE concept was “*in line with circular economy*” (AS06) and “*a good starting point*” (AS16) towards this goal because it only provides for the temporary storage of waste, while it is treated to enable the recovery of valuable materials (Sapsford et al., 2023), and others explained how it could help with the supply of raw materials:

> *It allows to create a new repository, a new order of some specific minerals. It should make these easily accessible and so this would support raw material supply with domestic resources.* (AS14)

The opportunity afforded through designing an environmentally neutral repository capable of producing recoverable materials was also seen as a political win:

> *For a local administration to be able to say, we can do away with this and we can have a fairly neutral landfill site that is producing recoverable materials. And has no overall net sort of disbenefit to the you know the environment or whatever that would be a massive political win for them.* (AS05)

Here, a ‘neutral landfill’ is referring to one with relatively inert waste where materials that remain largely unchanged over time, exhibiting no substantial physical, chemical, or biological alterations. These wastes do not dissolve, combust, react chemically or physically, or biodegrade, nor do they negatively impact other substances it contacts in a manner that could lead to environmental contamination or pose risks to human

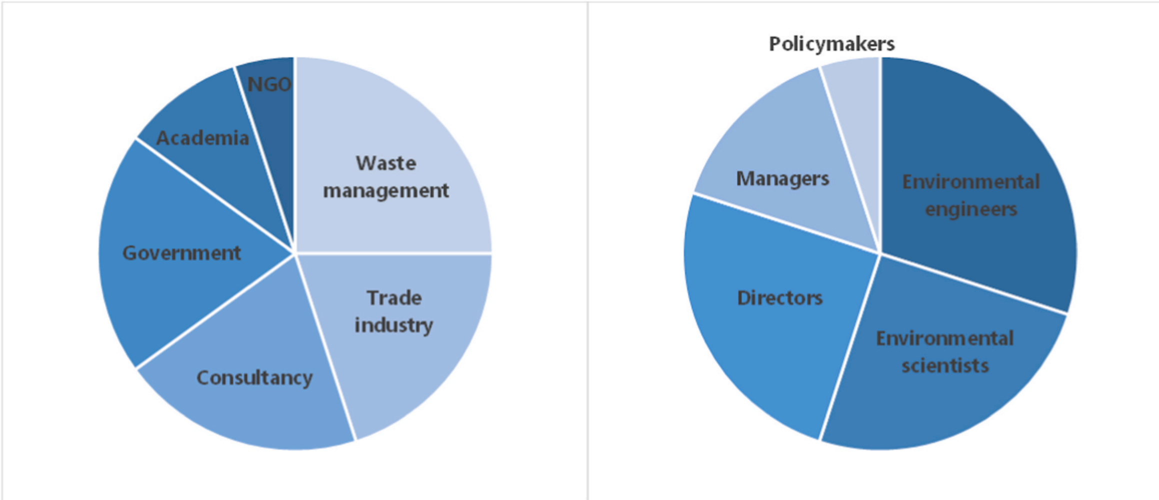

Fig. 1. Sector and role of the interview participants (n = 20).

health (Oujana and Sanchez, 2018).

However, these geopolitical factors can also act as barriers, for example, where resource nationalism inhibits investment (Nurmi, 2017), there is a variation in resource governance between countries (Cisternas et al., 2022) or the risk of companies relocating manufacturing (Velentruf and Purnell, 2021). The ASPIRE technology could mitigate some of these barriers, as the recovery of valuable materials could be carried out in importing countries (Cisternas et al., 2022), which would increase their resource security, particularly in countries dependent on imported materials.

Adoption of new technology is dependent on government action, and there are concerns that governments often do not think strategically, focusing instead on short-term priorities (Ali et al., 2017):

> *I like the concept, but I can't see it working for another decade. There's a lot of other things that are gonna happen before then because of the policy reforms and because of some of the imperatives around targets that are affecting other waste streams. I think you need a government message to enable us to be given some clarity that this is a space that's gonna take off.* (AS01)

Related to this, much of the action, in terms of recognising the risks to resource security and opportunities for resource recovery is taking place in research and intergovernmental organisations (e.g. UN) with governments being slow to act (Ali et al., 2017). The speed of change can be a barrier to the adoption of new technology by national and local government, for example:

> *Particularly so with local government, I think you get a lot of resistance to change because it just of the demographics of the structure of local government means it's not an organisation that adapts quickly to change.* (AS05)

Where new mineral extraction or waste repositories are required, land use planning is an important consideration (Carvalho et al., 2021), but politicians at the local level are often more concerned with other land use priorities and the negative perceptions of mineral extraction or waste disposal instead of recognising their strategic importance (Garnett et al., 2017). However, after uses that are seen as beneficial by the community, including recreational space or habitat creation are often viewed more favourably by local politicians. In fact, participants suggested that local governments could benefit from adopting the ASPIRE concept, for example:

> *The local authority will get a lot of positive feedback, from public, if they can see that they're improving the environment for people to use you know, because of ultimately these areas that I'm talking about are where people go for walks, they're hiking, walking their dogs.* (AS08)

> *For a local administration to be able to say, right, we can do away with this and we can have a fairly neutral landfill site that is producing recoverable materials and has no overall net sort of disbenefit to the environment - that would be a massive political win for them.* (AS05)

A further political consideration, related to economic factors (section 3.2) concerns who should pay both for the development of new technologies and the management of wastes; where public sector finances are constrained perhaps waste producers should bear these costs (Garnett et al., 2017). There are contrasting views on whether government interventions are necessary to encourage sustainable resource management or whether the markets will drive change (Machacek and Fold, 2014), for example:

> *Government has to encourage start-ups. The start-ups have to venture into the creation of marketplace. Once the marketplace gets created, the circular economy will follow.* (AS19)

3.2. Economic factors

Several economic factors were identified in the literature and corroborated by stakeholders with specific reference to the ASPIRE concept. Irrespective of the technology or type of resource new facilities require high levels of upfront investment (Dewick et al., 2019; Velenturf et al., 2019) or *"very big money, very quickly"* (AS11) and this is likely to be a barrier for the ASPIRE concept. The focus on rapid returns on investment can be a barrier (Jones and Comfort, 2018), particularly at a time when material prices are volatile (Buijs and Sievers, 2011; Ali et al., 2017; Kivinen et al., 2021); making likely returns difficult to estimate. There are also already considerable sunk costs in existing technologies (Hill, 2015) and ongoing operation (Dewick et al., 2019) and rehabilitation post-extraction or disposal also incur costs (de Vocht and Deschamps, 2011). These all represent significant risks for the ASPIRE concept; it is currently untested under field conditions and therefore would require substantial investment to demonstrate its efficacy, which may be perceived as too risky when mineral prices are unpredictable and there is uncertainty regarding the market for the product and the regulatory landscape (see below and section 3.5).

Where countries are reliant on importing materials, they are exposed to economic as well as political risks (Bartekova and Kemp, 2016; Silva et al., 2016; Carvalho et al., 2021; Cisternas et al., 2022). The global economy's dependence on critical metals could facilitate innovation (Ali

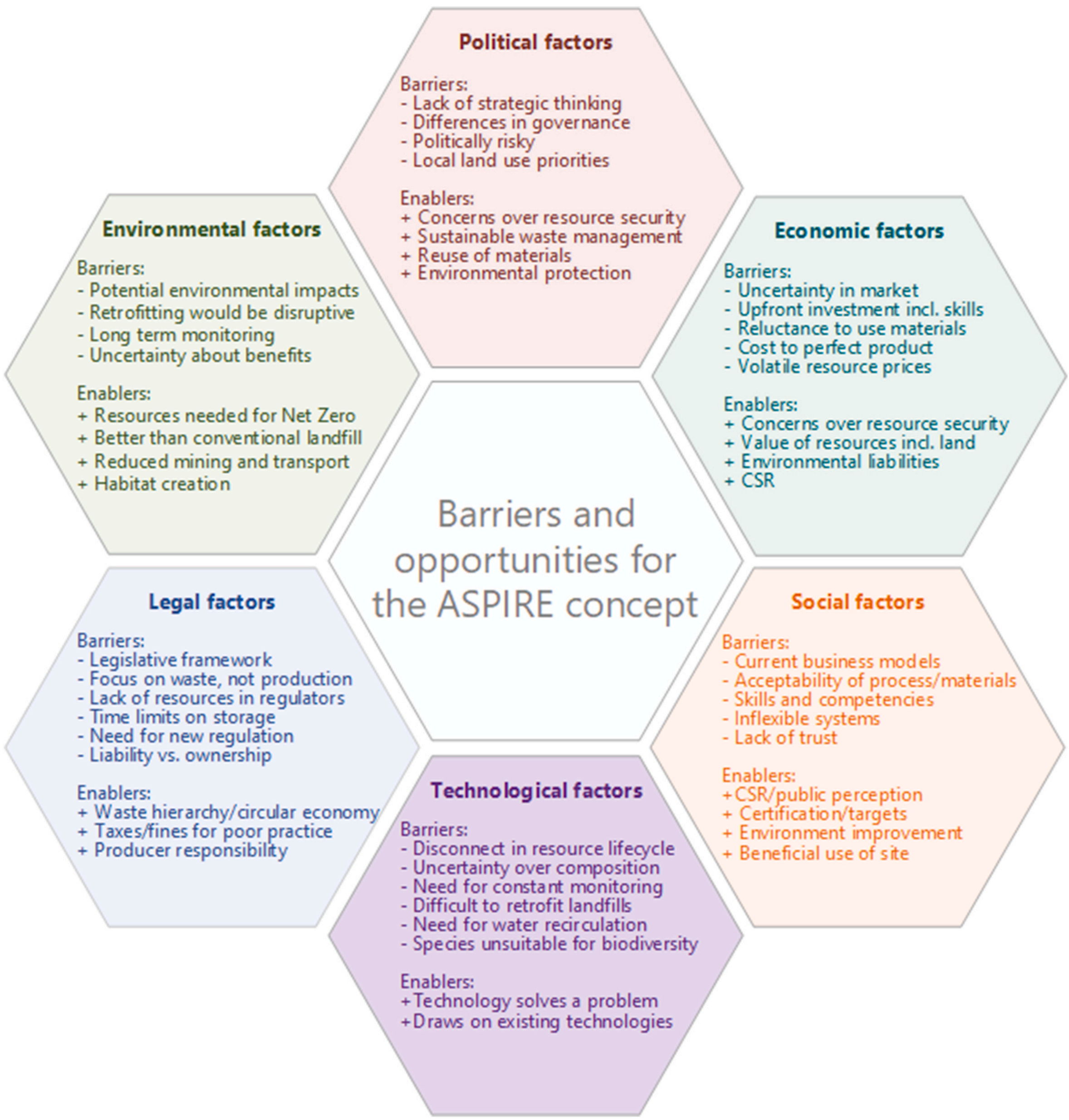

Fig. 2. PESTLE analysis of the ASPIRE concept.

et al., 2017) as raw material prices increase (Silva et al., 2016) and there is continued demand for e-tech materials to maintain our standard of living and transition to a low carbon economy (Bide et al., 2020; Janikowska and Kulczycka, 2021). As one participant explained:

> *We still gotta get the economic model right and prove the demand and work through the science. But ultimately, at some point we need to put the demand and the market and the economics together and go.* (AS01)

There is recognition that we need to increase our use of secondary sources of materials (Buijs and Sievers, 2011; Ajayi and Oyedele, 2017; EC, 2020), including through landfill mining (Silva et al., 2016; Burlakovs et al., 2017) and remining (Silva et al., 2016; Cisternas et al., 2022) and the ASPIRE concept may overcome some of the barriers associated with these:

> *It actually costs a lot of money to excavate it and process it. And often the quality can be a little bit poor.* (AS17)

Stakeholders also highlighted the economic value from extracted resource being a potential benefit of the ASPIRE concept, for example:

> *An awful lot of very useful materials that are currently sat there in landfills.* (AS13)

> *There are lots of opportunities for the businesses to be more resource efficient, decarbonize and economic opportunities to save money on, a you know, waste disposal if that waste can be more beneficially reused and valorised. And so a lot of opportunities there and particularly to have a more resilient supply chain, overall, material supply chain, if they're sourcing raw materials locally in a waste material instead of relying on imports.* (AS07)

Although upfront investment may be a barrier, this is also true of 'business as usual' approaches. Mineral extraction is subject to increasingly restrictive legislation (see section 3.5), which increases the investment required for new sites; the sector is rationalising at a time when demand is increasing and if this leads to increased prices then marginal deposits may become economically viable (Ali et al., 2017), which may make the ASPIRE concept a more attractive investment opportunity. Poor waste management also creates financial risks (Franks et al., 2011), and existing mechanisms including fines, taxes and charges (e.g. landfill tax) to penalise bad practices coupled with financial incentives (e.g. tax breaks) are effective at changing behaviours (Costa et al., 2010; Ajayi and Oyedele, 2017) and could shift the economic conditions towards the ASPIRE concept. For example, some stakeholders highlighted that it could *"bring an income for reuse"* (AS06) and reduce costs associated with waste management:

> *I'm not sure, but maybe this approach could reduce the waste management cost because as we say this is a lifelong lasting activity, so it doesn't stop with the mining activity.* (AS14)

Ultimately, the costs incurred need to be outweighed by the price of the commodities or the costs avoided (Prior et al., 2012). However, for this to be achieved we need to shift towards a value-based conception of waste (Van Ewijk and Stegemann, 2016) and market conditions need to change (Kivinen et al., 2021) to ensure there is demand for waste products (Velenturf et al., 2018). The EC Circular Economy Action Plan, for example, suggests mandating that products contain recycled materials could create a market for secondary raw materials. As one participant explained:

> *We're gonna need to demonstrate market demands is the other element to this. I think you know, do the chemical companies want this material and are they willing to pay for it?* (AS01)

If not, government policy needs to incentivise resource recovery (Silva et al., 2016) and sustainable disposal (Sheehan and Harrington, 2012) or provide direct funding to reduce the risk of investment until the technology can be self-sustaining (Costa et al., 2010). ASPIRE may mitigate some of the concerns of landfill mining, for example, the presence of hazardous wastes negatively impacts the viability of landfill mining (Burlakovs et al., 2017) whereas this could reduce the risks associated with hazardous waste. The economic benefits of landfill mining are often indirect (e.g. increased land value or capacity for waste) but it is possible to generate an income from recovered materials if there is a market and/or there are avoided costs (de Vocht and Deschamps, 2011; Burlakovs et al., 2017; Velenturf et al., 2018; Velenturf and Purnell, 2021).

3.3. Social factors

Social factors are those related to government and corporate practices, and the perceptions and experiences of stakeholders. Barriers include the lack of integration between government departments and the implementation gap between national policy and local delivery (Shiers et al., 2014). Beyond government, there are many stakeholders across the resource lifecycle, including policymakers, industry, NGOs, and trade organisations, but a lack of co-ordination and shared values between them (Sheehan and Harrington, 2012; Shiers et al., 2014; Silva et al., 2016; Dewick et al., 2019; Kivinen et al., 2021).

Additionally, the current governance of materials does not support resource recovery as materials change ownership through their lifecycle (Silva et al., 2016). Waste needs to be fully reconceptualised as a resource, with closed loop value chains (Wårell, 2021; Wilts et al., 2016) supported by a global governance structure for resources that can be implemented locally (Silva et al., 2016; Shiers et al., 2014). This requires a long-term strategic commitment that is co-created by all stakeholder groups (Hill, 2015; Cisternas et al., 2022).

Other barriers include ensuring appropriate skills, knowledge and competencies exist across industry and regulators (Dewick et al., 2019; Sheehan and Harrington, 2012; Velenturf et al., 2019), as one participant explained there will be:

> *… competencies that will be required for managing those types of sites and which qualifications would they expect to have.* (AS04)

There is social pressure for corporate behaviour change (Tayebi-Khorami et al., 2019; Santiago et al., 2021). Trade organisations, like the Global Mining Initiative and the International Council on Mining and Metals have already adopted principles for responsible mineral production, which include reducing waste and increasing re-use and recycling (Franks et al., 2011; Tayebi-Khorami et al., 2019). Furthermore, existing certification schemes and targets have driven changes in industry and consumer behaviours (Sheehan and Harrington, 2012; van Ewijk and Stegemann, 2016). Therefore, the ASPIRE concept could capitalise on an industry looking for solutions (Franks et al., 2011) and to demonstrate Corporate Social Responsibility (CSR) (Jones and Comfort, 2018):

> *Quite often, companies like mine will reduce the profits that they make on that project because it has loads of other benefits. The benefit is it helps us, as a company, demonstrate our credentials as being sustainable.* (AS08)

This could relate to measures to create a market for materials from the ASPIRE concept, including advertising the products that have been manufactured using secondary raw materials, or demonstrating the business has adopted the ASPIRE concept to ensure their repositories are more sustainable than engineered landfills. As with any new technology, stakeholders highlighted that barriers associated with acceptance of the ASPIRE concept are likely to be significant and increase the perceived risk associated with investment in the technology:

> *In construction, there's reluctance for people to try something new because it presents an unquantified risk. I would say that's always going to be the biggest barrier is perception of risk, but then also you find that you've got to change people's mindset, cause sometimes using alternative materials can be less efficient and so make people's lives more difficult.* (AS20)

In addition to the risk associated with the acceptability of the materials, there are also risks related to the presence of the ASPIRE repository and the impact it may have on the locality. Communities may be concerned about the impact of the ASPIRE repositories on the environment, their health or property prices (Lamb et al., 2014; Pimentel et al., 2016; Tayebi-Khorami et al., 2019; Dewick et al., 2019), especially given the lack of trust in industry and public officials (Garnett et al., 2017; Nurmi, 2017). Participants anticipated difficulties in generating support for the concept, as well as suspicion and resistance from the public, related to concerns about landfill mining:

> *I could imagine that locally … no one wants to have a landfill mining operation in their backyard. It will not be pleasant. It'll be smelly and very hard to control anyway, so I can imagine that would be a challenge.* (AS15)

As with any new facility, proactive and effective stakeholder engagement will be required early to understand the perspectives of residents and businesses, develop a shared vision and secure a social license to operate (Erzurumlu and Erzurumlu, 2015; Santiago et al., 2021; Wårell, 2021). However, residents can be sceptical of engagement processes (Tayebi-Khorami et al., 2019; Santiago et al., 2021) and this will be especially important for a new technology to ensure its acceptability (Franks et al., 2011; Garnett et al., 2017; Szabó et al., 2017). It may be that there would be greater public support for an ASPIRE repository compared with a conventional landfill if it is seen as more advanced and environmentally friendly (Garnett et al., 2017), especially if it can be combined with after-uses that promote nature and recreation (Benyamine et al., 2004; Szabó et al., 2017). Participants also felt there could be an opportunity to adopt the ASPIRE concept for legacy wastes and improve the environment for people, but the way it is classified and presented to communities could impact on the acceptability:

> *If it's classed as treatments rather than a landfill activity than that kind of helps people. You know, not viewing it as landfill. It (…) shows that you're making best attempts to avoid landfill.* (AS04)

> *It's getting people to understand. Explaining exactly how we reach the end products, what happens at the very end, how the facility operates. I think helps that definition of a circular economy.* (AS05)

However, others felt that there is not currently an appetite to recover waste from legacy landfills, due to the impact on local people and uncertainty over the material:

> *In terms of opening up all the landfills at the moment, they were saying there's absolutely no way it would do that because, one, is the smell. That's, you know, the one thing that they have is a nightmare PR disaster for them is a smell. And two is that lots of people don't actually know what has been thrown in there pre-1990.* (AS10)

3.4. Technological factors

Technological factors are likely to provide opportunities for the ASPIRE concept as industry is looking for solutions to several global challenges. Solutions that reduce the environmental impact of waste materials (Cisternas et al., 2022) and increase the recovery of resources from wastes are likely to be viewed positively (Buijs and Sievers, 2011; Prior et al., 2012; Jones and Comfort, 2018) as the supply of raw materials declines. Participants also felt that the ASPIRE concept provides a technological answer to a pressing problem and therefore was perceived by the stakeholders as a substantial opportunity.

However, technological development is driven by economic conditions (Prior et al., 2012), and we are perhaps not yet in a position where these conditions support the ASPIRE concept (see section 3.2). Particularly given the governance issues and the focus on technologies to manage waste (Cisternas et al., 2022) as opposed to those which prevent waste.

The heterogeneous nature and spatial distribution of many industrial wastes are also barriers as it is challenging to assess their potential for resource recovery (Sheehan and Harrington, 2012; Ajayi and Oyedele, 2017; Burlakovs et al., 2017; Bide et al., 2020; Žibret et al., 2020):

> *That would be a real problem. Big problem is, you really have very little knowledge. What's in there? And it's quite variable.* (AS15)

> *It's just whether it is feasible because obviously dredgings can contain a large amount of different contaminants.* (AS04)

There needs to be certainty regarding the composition and grade of any resources that are recovered (Machacek and Fold, 2014; Bide et al., 2020) to overcome negative perceptions of materials. In an ASPIRE repository it would also be important to ensure that any biogeochemical engineering has not altered the properties of the materials (Dewick et al., 2019) and it is likely that international standards will be required to demonstrate quality of the recovered materials (Costa et al., 2010; Ali et al., 2017). Participants also highlighted that quality of the extracted materials is uncertain and some industries (e.g. construction) are reluctant to use recycled materials. They also related this to the economic viability of the technology, where the cost to perfect the resource may substantially increase costs:

> *Whether the quality of the material is the same as new materials. For instance, if you add it to a new concrete or whatever, how? How will the quality be? (…) It also depends what you're building. And there are certain things that you can't build with recycled materials. Maybe you need to make a different choice of material depending on what you're building.* (AS17)

There is also currently a spatial disconnect between extraction, processing and waste production (Ali et al., 2017), which hinders adoption of circular economy approaches. For example, there may be a mismatch between the volume of critical materials recovered and the demand (Machacek and Fold, 2014), the volume necessary for commercialisation (Žibret et al., 2020) or the location of waste production and resource use. Participants also highlighted that in the UK it is very challenging to find sites for new landfills:

> *Looking for a new landfill, so it can actually be incorporated, is probably quite difficult.* (AS09)

There are specific challenges in waste repositories that would need to be considered, including the toxicity of leachates to plant species (Benyamine et al., 2004). For example, species tolerant to leachates may not be those that produce lixiviants or are appropriate for site conditions or desired after uses (Lamb et al., 2014). In England, the new Biodiversity Net Gain regulations (Environment Act, 2021) will force a consideration of habitat creation, whereas often this is secondary to the engineering (Benyamine et al., 2004).

There would also need to be a shift in thinking regarding water management, currently waste repositories are designed to reduce water infiltration to minimise the production of leachates or seepage (Franks et al., 2011; Szabó et al., 2017), whereas in the ASPIRE system water would need to filter through to ensure the plant lixiviants enter the waste. There is precedent for this approach in bioreactor landfills, but the hydrology of the wastes would require careful design, and this adds to the risks associated with a new technology highlighted above.

Landfill mining and waste reprocessing are happening (Burlakovs et al., 2017; Cisternas et al., 2022) which perhaps increases the appetite for similar technologies such as the ASPIRE concept, although *"even retrofitting will have its difficulties"* (AS09). The most pressing technological barrier expressed by the participants was the uncertainty of how the ASPIRE system would work in practice, as it is currently being testing in experimental settings.

> *Something that's quite difficult to quantify, but it is confidence and understanding. As soon as you know this is good across all scientific concepts … and it's probably as old as time really, as soon as you introduce something new, people don't understand it. Then they mistrust it.* (AS05)

3.5. Legal factors

There are significant regulatory barriers related to the ASPIRE concept. Despite resource recovery and reuse being a high-level policy there is a lack of supportive regulation (van Ewijk and Stegemann, 2016; Janikowska and Kulczycka, 2021), which tends to consider materials as wastes (Costa et al., 2010; Janikowska and Kulczycka, 2021). As one participant explained:

> *Now we have the technology to solve the problem that needs a whole regulatory reform to enable it to happen, to make it a viable opportunity.* (AS01)

Generally, legislation centres on the waste hierarchy and/or reducing negative environmental impacts as opposed to cleaner production, the potential value of materials or ecosystem stewardship and this hinders recovery and reuse (van Ewijk and Stegemann, 2016; Velenturf and Purnell, 2021; Wilts et al., 2016; Dewick et al., 2019; Costa et al., 2010). Furthermore, targets measuring progress are linked to waste management (e.g. reduction in landfilling, increased recycling) as opposed to value creation, reuse, or prevention (Wilts et al., 2016) and participants suggested that the technology could help achieve targets related to diverting waste from landfills to alternative treatments.

Existing mineral extraction or waste management regulation is complex and inflexible to considering the potential for resource recovery (van Ewijk and Stegemann, 2016; Dewick et al., 2019; Tayebi-Khorami et al., 2019). Although it is possible to classify some industrial wastes as by products, the requirement for these to be produced through 'normal' processing (Dewick et al., 2019) may be a barrier. Similarly, waste materials can meet 'end of waste criteria' at the end of a recovery operation when it is ready for its final intended use (Environment Agency, 2024). Dewick et al. (2019) found an appetite for a 'third way' between landfill disposal and resource recovery where the latter are stored in the longer term for use later. However, they acknowledge that such an approach would need a change in legislation so that such materials could be stored for longer than is currently permissible for by-products with an intended use; this same principal could apply for ASPIRE. For example:

> *You've got two issues with the landfill regulations and the landfill disposal tax regulation in terms of storage … we need to find a way to incentivise the use of that material and if it needs to be stored and there can be a fairly certain that there will be a way found to deal with it, then that needs to be explored.* (AS07)

There are policy 'hooks', which could act as opportunities, for example the UK's Resource Security Action Plan (BIS and Defra, 2012) and EC's Circular Economy Action Plan (EC, 2020) prioritise efficient resource use and minerals safeguarding requires local authorities to develop plans for their area, including recovery from legacy mine wastes (MHCLG, 2014; Carvalho et al., 2021). In England the Environment Act, 2021 places greater expectation on producer responsibility, which could also be an important enabler to elicit change (Velenturf and Purnell, 2021; Wilts et al., 2016). Regulations can also impose punitive taxes to increase the costs of undesirable practices (e.g. landfill taxes) or provide incentives (e.g. tax breaks) to encourage a change or ensure the quality of the process and resultant materials (Costa et al., 2010; Hill, 2015; Dewick et al., 2019; Velenturf and Purnell, 2021).

The interpretation of the regulation by officers who are under-resourced (Dewick et al., 2019) and perhaps do not have expertise in new technologies is also a barrier. Permits were highlighted as a specific issue in the UK:

> *They [regulators] struggle to manage any requests for new permits on modifications to permits.* (AS04)

> *I think our legislative framework around landfills doesn't help. The ASPIRE approach is medium term, 20–30 years waste. The regulators are not going to allow that to happen without having a permit and all the things that go with permits, monitoring, restoration plans and everything in place.* (AS02)

Related to the social barriers, the lack of reassurance provided by regulation would mean the technology is risky in terms of liability, ownership, environmental performance and the resource:

> *I don't think there's any sort of rules just to ensure the quality (of the extracted materials).* (AS03)

> *There's all sorts of questions about the risks, practicality. Who owns the material in there? Who makes the money out of it? Aside from the technical difficulties of making it work, which are one thing, there's an awful lot of administrative and legal and liability issues that need to be resolved.* (AS02)

3.6. Environmental factors

Finally, environmental factors understandably present a barrier to any waste management or mining operation (Sheehan and Harrington, 2012; Erzurumlu and Erzurumlu, 2015; Ali et al., 2017; Carvalho et al., 2021). Conventional landfills can cause negative environmental impacts including leachates and effluents causing soil, ground and surface water contamination (Lamb et al., 2014; Burlakovs et al., 2017; Cisternas et al., 2022). This means that new solutions for waste disposal are sought (Carvalho et al., 2021), particularly for industrial wastes currently deposited on land (e.g. dredgings; Leotsinidis et al., 2018) or where landfills are posing an environmental hazard (Burlakovs et al., 2017). The ASPIRE concept would need to satisfy environmental regulations, which may pose a technical challenge on legacy wastes where there is uncertainty about the composition of wastes and variability in the leachates (Burlakovs et al., 2017):

> *Some of the landfill leachate systems can be quite complex in there. Whatever you're extracting, you may have some unintended environmental consequences associated because you have different pools in areas, and you've got all the technical challenges and the big pockets of methane. Whenever you're certain to move around, it changes the leach.* (AS15)

If the ASPIRE concept can satisfy regulatory and stakeholder requirements, some of the social factors identified could act as environmental opportunities. For example, there could be opportunities to achieve accreditation for designing out waste if materials stored in ASPIRE systems are used in products (Ajayi and Oyedele, 2017). It also aligns with industry codes to reduce environmental impacts during operation and aftercare (Franks et al., 2011) and CSR strategies and commitments (Jones and Comfort, 2018) towards the circular economy:

> *If you're pulling out rare chemical compounds, potentially high value declining resources, even if they're small amounts, they're still making a contribution to this ever-increasing circularity.* (AS01)

There are further opportunities related to the reduced environmental impact from new mines (Buijs and Sievers, 2011; Burlakovs et al., 2017; Cisternas et al., 2022) and more sustainable resource management (Ali et al., 2017). Some stakeholders mentioned the potential for lower carbon emissions if the materials are not currently extracted in the UK:

> *From an economic perspective, if we're gaining materials that are difficult to extract or are not necessarily found within the UK or if you're shipping them across the world, then you will benefit, carbon emissions or whatever.* (AS05)

Given the strict environmental regulations in many places, the ASPIRE concept could be most beneficial where there are poor waste management practices (Burlakovs et al., 2017), uncovered wastes (Franks et al., 2011), legacy mine sites (Pimentel et al., 2016) and dredgings (Leotsinidis et al., 2018; Sheehan and Harrington, 2012).

Landfill restoration can already achieve biodiverse or novel ecosystems and places for recreation (Benyamine et al., 2004; Lamb et al., 2014), often gaining public support (Benyamine et al., 2004; Erzurumlu and Erzurumlu, 2015). However, some sites are not beneficial for biodiversity due to the composition of leachates, wastes or cover materials (Benyamine et al., 2004; Song, 2018). Long term habitat creation is possible with landfill mining (de Vocht and Deschamps, 2011; Burlakovs et al., 2017). However, it is preferable to plan this from the outset as mining landfills is disruptive to ecosystems (de Vocht and Deschamps, 2011) and nearby residents. The greatest opportunity to incorporate the ASPIRE concept is therefore in the design phase of landfill engineering or mining operations so that resource recovery and habitat creation is 'built in'. Participants also described how the concept could be seen as an opportunity to develop natural reserves on site:

> *A lot of those people are interested or concerned about what they're gonna do with their landfills after they're finished and, in quite a few instances, some larger companies have turned them into nature reserves as well (…) They've created quite a nice space for people to walk dogs and look at wildlife.* (AS15)

> *When I worked at the landfill site, it was an abundance of wildlife there. It was really surprising. If you put something up like that, I think you probably find that there are ecological benefits that we don't know exist yet.* (AS05)

Stakeholders also mentioned that what appears to be a solution now, may mean an issue in the future:

> *Maybe the chemical you put into it will be another problem. We use the polymer to modify the soil to improve its characteristics or engineering properties. But I think maybe in the future it will be another problem.* (AS18)

Finally, there is challenge in the long-term monitoring of waste disposal and mining sites for their environmental impacts (Nurmi, 2017; Pimentel et al., 2016), which are likely to be greater for a new technology:

> *This [technology] not gonna be a quick process. This is something that's going to need to be monitored and managed very, very closely. Sampling, will have to be constantly taken.* (AS06)

4. Limitations

The study has several limitations. First, the ASPIRE concept is in its infancy and therefore lacks technical detail and long-term field scale evaluations. This means that participants were asked to provide their perspectives on the potential for a concept for which information is lacking. However, it is important to anticipate what barriers exist at the early stage of technology development, especially where these will also hamper further development. Second, in our data, there is a notable UK bias among the participants, which may limit the broader applicability of the concept. Our analysis is primarily dominated by perspectives from the waste industry, with no input from residents, product designers, or users of materials. This narrow focus may overlook important considerations from other stakeholders, which are essential to the successful adoption and integration of ASPIRE.

5. Conclusions

This paper provides the first in-depth exploration of the viability of the ASPIRE waste repository concept, extending the analysis beyond technical considerations to include a broader examination of factors through a PESTLE analysis.

The findings underscore the interconnectedness between these factors. The viability of the ASPIRE concept hinges on favourable political and economic conditions, which are critical for driving investment and technological advancement. Public perception and stakeholder engagement are equally crucial, as they directly influence political support and social acceptance - both vital for the adoption of this novel technology. Environmental considerations are central to the ASPIRE concept, as the technology aims to contribute to sustainability efforts and the transition towards a circular economy. Demonstrating clear environmental benefits will be critical for securing political will, gaining public trust, and justifying the necessary investments. The regulatory environment also plays a pivotal role in shaping the economic, technological and environmental feasibility of ASPIRE, with legislative reforms needed to fully unlock its potential. This interconnectedness also highlights that addressing a single factor in isolation is insufficient; a holistic approach focused on reducing uncertainty and risk is essential for the successful development and implementation of the ASPIRE concept. To achieve this, securing political will, demonstrating environmental benefits and investing in both development and supportive legislation are paramount. These efforts will likely catalyse cultural aspects, further driving social acceptance.

Uncertainties remain, particularly concerning the scalability of the technology, which necessitates field-scale testing to assess its commercial viability. The outcomes of this research are clear: overcoming significant social and environmental barriers requires a collaborative approach, as it is unrealistic for research or industry to tackle this challenge alone. Prioritising collaborative efforts across government and industry is crucial, along with engagement with the public; failure to do so risks missing the opportunity to recover resources to meet growing resource demands, enhance environmental sustainability, and ultimately advance towards a circular economy.

CRediT authorship contribution statement

Ana Margarida Sardo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Danielle Sinnett:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Nia Elin Owen:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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