Waste Management under Structural Constraints: Efficiency, Policy Reform, and Recycling Performance in Iceland

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Thesis for the degree of PhD
in Environment and Natural Resources

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School of Social Sciences

FACULTY OF BUSINESS ADMINISTRATION

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VIÐSKIPTAFRÆÐIDEILD

HÁSKÓLI ÍSLANDS

To my children

Guðný Rósa

and

Jóhannes Berg

In the loving memory of

Dr. Fríða Jóhannesdóttir

"Everything that is in the heavens, on earth,
and under the earth is penetrated with
connectedness, penetrated with relatedness"

— Hildegard von Bingen

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Ágrip

Ísland einkennist í alþjóðlegum samanburði af smæð, strjálbýli og dreifðri byggð. Í þessari doktorsritgerð er lagt mat á hvernig tekist hefur að innleiða opinbera stefnumótun á sviði úrgangsmála hjá íslenskum sveitarfélögum. Sérstök áhersla er lögð á árangur endurvinnslu og skilvirkni skipulagsbreytinga, með tilliti til þeirra skorða sem innviðir og skipulag sorpmála setja. Rýnt er í þá umbreytingu sem átti sér stað árið 2023 þegar farið var úr ósamræmdu kerfi, sem einkenndist af skipulagslegum hindrunum, yfir í samræmt kerfi sem byggir á lögum um hringrásarhagkerfi og aukinni framleiðendaábyrgð (e. Extended Producer Responsibility, EPR). Greiningin tekur mið af landfræðilegum og lýðfræðilegum skorðum, fyrirkomulagi stjórnsýslu og flokkunarhegðun almennings sem samverkandi þáttum í einu heildstæðu kerfi.

Í stað þess að líta á innleiðingu stefnu sem samfellt línulegt ferli, er hér lagt til að árangur hringrásarhagkerfis ráðist af þrepaskiptu mótunarferli (e. hierarchical filtering mechanism). Mat á skilvirkni með gagnaumhverfisgreiningu (e. Data Envelopment Analysis) ásamt hagfræðilegum greiningum sýnir að strjálbýli og lýðfræðilegur breytileiki, sér í lagi árstíðabundin ferðaþjónusta, setja kerfinu harðar ytri skorður. Frávik frá væntum árangri, sem hefðbundnir mælikvarðar túlka oft sem óskilvirkni í stjórnun, endurspegla fremur takmarkaða innviði, áskoranir í flutningi úrgangs í norðlægu umhverfi og þjónustuþörf umfram skráðan íbúafjölda (e. denominator bias).

Þótt umbæturnar árið 2023 hafi aukið og samræmt fjárhagslega ábyrgð framleiðenda héldu sveitarfélög áfram ábyrgð á skipulagi sorphirðu. Fyrstu greiningar á áhrifaþáttum endurheimtar úrgangsefna með grárri tengslagreiningu og hagfræðilegum aðferðum (e. Grey Relational and Econometric Approaches), ásamt rofinni tímaraðagreiningu (e. Panel Interrupted Time Series) á samsetningu úrgangs í almenna sorpílátinu, sýna að samræming kerfa skilar ekki einsleitum árangri. Innleiðing hins lögbundna fjögurra flokka kerfis við heimili varð mikilvægur snertiflötur milli stefnumótunar og heimila og tengdist skýrum kerfislægum þáttaskilum í magni lífbrjótanlegs eldhúsúrgangs sem eftir var í almenna sorpílátinu. Engu að síður sýna niðurstöðurnar að áhrif umbótanna ráðast að verulegu leyti af staðbundnum innviðum og þeim landfræðilegu aðstæðum sem sveitarfélög búa við.

Til að setja þessar niðurstöður í víðara samhengi er sett fram samþætt fjögurra stiga líkan. Líkanið varpar ljósi á hvernig landfræðilegar aðstæður móta hvernig stefnumótun og stjórnsýsla skila sér í þjónustuinnviðum og þar með í raunverulegan árangur kerfisins. Meginniðurstaða ritgerðarinnar er sú að í smáum og dreifðum sveitarfélögum dugar samræmt regluverk ekki eitt og sér, þótt það sé nauðsynleg forsenda framfara. Til að hringrásarhagkerfi nái árangri þurfa innviðir og þjónusta jafnframt að vera

sérstaklega aðlöguð að staðbundnum aðstæðum. Niðurstöðurnar hafa hagnýtt gildi við mótun árangursmælikvarða, fjármögnunarfyrirkomulags og söfnunarkerfa á svæðum sem búa við ólíkar landfræðilegar aðstæður. Þótt greiningarramminn sé þróaður út frá íslenskum aðstæðum kann hann að hafa yfirfærslugildi fyrir önnur smá, eyja-, norðurslóða- og afskekkt svæði þar sem innleiða þarf sameiginleg markmið hringrásarhagkerfisins við mjög ólíkar landfræðilegar og þjónustutengdar aðstæður.

Lykilorð:

Úrgangur sveitarfélaga, hringrásarhagkerfi, framleiðendaábyrgð, landfræðilegar takmarkanir, flokkunarhegðun heimila.

Abstract

This doctoral thesis evaluates the efficiency, policy translation, and recycling performance of municipal waste management systems in Iceland, a small and geographically dispersed Arctic economy. Based on an integrated multi-method research design, the thesis examines the transition from a fragmented and structurally constrained system toward a harmonised framework underpinned by an expanded Extended Producer Responsibility (EPR) mandate and the 2023 "Circular Law."

Rather than viewing policy implementation as a linear process, the thesis proposes that circular economy outcomes emerge through a hierarchical filtering mechanism. Combined efficiency analysis (Data Envelopment Analysis) and econometric modelling demonstrate that geographic dispersion, demographic volatility, and seasonal tourism act as binding structural constraints. What standard performance metrics often interpret as managerial inefficiency instead reflects the operational friction of Arctic logistics and systematic denominator bias.

While the 2023 reform expanded and harmonised producer-financed responsibility, municipalities retained responsibility for organising collection services. Analyses of early recovery determinants using Grey Relational and econometric approaches, together with panel Interrupted Time Series analysis of residual-waste composition, show that institutional harmonisation does not produce uniform outcomes. The rollout of the mandatory four-bin source-separation system served as a critical household-facing operational interface and was associated with a structural break in the amount of biodegradable kitchen waste remaining in the general bin. However, the magnitude of these outcomes remained conditioned by local infrastructure configuration and spatial constraints.

To synthesise these findings, the thesis develops an integrated four-level socio-technical framework. The framework shows how structural geography (Level I) filters how institutional design (Level II) is translated into operational infrastructure (Level III) and, ultimately, realised system outcomes (Level IV). The thesis concludes that in geographically heterogeneous environments, harmonised regulatory frameworks are necessary but insufficient; achieving a circular economy requires infrastructure systems that are explicitly adapted to local spatial conditions. The findings have practical relevance for the design of performance metrics, financing arrangements, and collection systems in geographically heterogeneous jurisdictions. Although developed from the Icelandic case, the analytical framework has potential transferability to other small, island, Arctic, and remote regions where common circular economy objectives must be implemented under markedly different spatial and service conditions.

Keywords:

Municipal Solid Waste, Circular Economy, Extended Producer Responsibility (EPR), Spatial Constraints, Household Separation Behaviour.

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List of Abbreviations

CE	Circular Economy.
DEA	Data Envelopment Analysis.
DMU	Decision-Making Unit.
EEA	European Economic Area.
EPR	Extended Producer Responsibility.
EU	European Union.
EWC-Stat	European Waste Classification for Statistics.
GDP	Gross Domestic Product.
GRA	Grey Relational Analysis.
ITS	Interrupted Time Series.
MLP	Multi-Level Perspective.
MSW	Municipal Solid Waste.
OECD	Organisation for Economic Co-operation and Development.
OLS	Ordinary Least Squares.
UNEP	United Nations Environment Programme.
VIF	Variance Inflation Factor.
VRS	Variable Returns to Scale.

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List of Original Papers

The thesis is based on the following original publications, which are referred to in the text by their Roman numerals (I-IV).

I. Óskarsson, G. K., Agnarsson, S., & Davíðsdóttir, B. (2022). Waste management in Iceland: Challenges and costs related to achieving the EU municipal solid waste targets. Waste Management, 151, 131–141. https://doi.org/10.1016/j.wasman.2022.07.035.

II. Óskarsson, G. K., Agnarsson, S., & Davíðsdóttir, B. (2025). Evaluating municipal solid waste management efficiency in Iceland: A data envelopment analysis of socioeconomic and geographic influences. Environmental and Sustainability Indicators, 26, 100676. https://doi.org/10.1016/j.indic.2025.100676.

III. Óskarsson, G. K., Agnarsson, S., & Davíðsdóttir, B. (2026). Early Determinants of Packaging Waste Recovery under Iceland's 2023 EPR Reform: Evidence from Grey Relational and Econometric Analysis. Environmental and Sustainability Indicators, 30, 101144. https://doi.org/10.1016/j.indic.2026.101144.

IV. Óskarsson, G. K., Agnarsson, S., Davíðsdóttir, B., & Ingason, H. T. (2026). Source-separation infrastructure and the reduction of residual household waste: Evidence from Iceland's 2023 waste reform. Waste Management, 226, 115809. https://doi.org/10.1016/j.wasman.2026.115809

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Declaration of Contribution

Paper I. Waste management in Iceland: Challenges and costs related to achieving the EU municipal solid waste targets

GKÓ: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation. SA: Writing – review & editing, Supervision, Methodology, Conceptualisation. BD: Writing – review & editing, Supervision.

Paper II. Evaluating municipal solid waste management efficiency in Iceland: A data envelopment analysis of socioeconomic and geographic influences

GKÓ: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation. SA: Writing – review & editing, Supervision, Methodology. BD: Writing – review & editing, Supervision.

Paper III. Early Determinants of Packaging Waste Recovery under Iceland's 2023 EPR Reform: Evidence from Grey Relational and Econometric Analysis

GKÓ: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation. SA: Writing – review & editing, Supervision, Methodology, Conceptualisation. BD: Writing – review & editing, Supervision, Conceptualisation.

Paper IV. Source-Separation Infrastructure and the Reduction of Residual Household Waste: Evidence from Iceland's 2023 Waste Reform.

GKÓ: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation. SA: Writing – review & editing, Supervision, Methodology, Conceptualisation. BD: Writing – review & editing, Supervision. HÞI: Writing – review & editing, Supervision.

During the preparation of this thesis, the author used Grammarly and Gemini/ChatGPT to improve the readability and language of this manuscript. The content in this manuscript is original input from the author. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the thesis's content.

1 Introduction

The transition from a linear "take–make–dispose" economy to a circular economy (CE) represents one of the most significant sustainability transformations of the 21st century (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017; Kirchherr et al., 2017). In contrast to linear disposal logic, circular economy approaches aim to preserve value in material stocks through reuse, repair, and remanufacture, and to treat post-consumer waste as a recoverable resource rather than an unavoidable externality (Ghisellini et al., 2016; Stahel, 2016). Across Europe, this paradigm shift has been operationalised through increasingly stringent recycling targets, landfill restrictions, and Extended Producer Responsibility (EPR) systems with the objective of decoupling resource use and environmental pressure from economic growth (European Commission, 2020; UNEP, 2011).

However, the circular economy is not only a technical transition driven by targets and financing. It is also a governance challenge, and scholars have cautioned that the concept can remain normatively attractive while empirically under-specified and insufficiently tested under real-world constraints (Korhonen et al., 2018). One such constraint is territorial asymmetry. Waste governance does not operate in spatial neutrality: in small island and Arctic economies, low population density, long transport distances, settlement dispersion, and demographic volatility shape cost structures and service delivery conditions in ways that differ fundamentally from continental urban systems (Eckelman et al., 2014; Eisted & Christensen, 2011; Keske et al., 2018). When uniform policy instruments are applied across heterogeneous territories, differentiated outcomes may emerge not because of managerial inefficiency, but because of exogenous spatial constraints.

Iceland offers a particularly revealing case for examining these dynamics. In this thesis, Iceland is treated as an Arctic and sub-Arctic case in a socio-spatial rather than strictly latitudinal sense. Although most of the country lies south of the Arctic Circle, Iceland is formally one of the eight Arctic States, and the Arctic Circle crosses Grímsey off the north coast (Arctic Council, 2026). The relevance of the Arctic framing here lies particularly in the combination of low population density, long transport distances, dispersed settlements, climatic exposure, and peripheral service conditions that Iceland shares with other northern regions. Historically, municipal waste generation has closely tracked macroeconomic drivers such as Gross Domestic Product (GDP) and population growth, reflecting a material flow structure in which economic expansion translates directly into increased refuse (Óskarsson et al., 2022). As a member of the European Economic Area (EEA), Iceland is legally obligated to implement the European Union

(EU) waste directives and progressively stricter recycling and landfill diversion targets (European Commission, 2018, 2020). However, with approximately four inhabitants per square kilometre and substantial distances between settlements, Iceland operates under logistical conditions fundamentally different from most continental EU member states. For the purposes of this thesis, a municipality refers to a legally constituted local-government unit with an elected local authority and responsibility for its own affairs. Municipalities are legal entities under Icelandic law and may cooperate with one another in delivering services that are difficult or inefficient to provide independently (Local Government Act No. 138/2011). Rapid tourism growth has also generated high seasonal occupancy intensity that exceeds registered residents in several municipalities, complicating per-capita performance metrics and straining local infrastructure (Arbulú et al., 2024; Caponi, 2022). In tourism-intensive regions such as Iceland, municipal waste indicators based on resident population may be affected by service-population denominator bias, whereby the effective population served by waste collection systems differs substantially from the registered population. These characteristics create a central governance tension: Can harmonised circular economy policies produce equitable and efficient outcomes in a geographically dispersed Arctic context?

This thesis argues that the effectiveness of circular economy reform depends not solely on regulatory ambition or financial design, but on the interaction between institutional instruments and underlying spatial conditions. Geography shapes the feasible efficiency frontier within which municipalities operate; institutional design redistributes financial responsibility; infrastructure configuration translates policy into operational practice; and behavioural outcomes strongly influence realised recovery performance (Andersson & Stage, 2018; Struk, 2017). By conceptualising municipal waste management as a structurally conditioned socio-technical governance system, the thesis integrates insights from spatial economics, public finance, efficiency analysis, and behavioural policy. The central claim is that harmonised circular economy reform can redistribute fiscal burdens and accelerate behavioural adaptation; however, it does not neutralise the spatial diseconomies that condition operational efficiency. Instead, structural geography acts as a filter mechanism, mediating how policy intent translates into realised outcomes.

Empirically, the thesis consists of four interconnected studies that examine Iceland's transition from a fragmented, landfill-dependent system to a harmonised producer-funded framework and mandatory four-bin collection. Using comparative cost analysis, Data Envelopment Analysis (DEA) (Rogge & De Jaeger, 2012; Simões et al., 2010, 2012; Worthington & Dollery, 2001), Grey Relational Analysis (Deng, 1989; Javanmardi et al., 2020), econometric modelling, and panel Interrupted Time Series (ITS) design (Lopez Bernal et al., 2016; Wagner et al., 2002), the studies examine structural, institutional, infrastructural, and behavioural effects. It is important to note that while the panel ITS design employed in the final stage of the research allows for the identification of quasi-experimental structural breaks, the methodologies applied in

the earlier stages establish robust structural associations. Therefore, the integrated framework presented in this thesis proposes a theoretical causal model, supported by an accumulation of associative, descriptive, and quasi-experimental evidence. Together, the findings contribute to the literature in three principal ways. First, they demonstrate that efficiency benchmarking in sparsely populated territories must explicitly control for geographic conditions to avoid conflating constraint with inefficiency. Second, they show that while EPR systems can address fiscal asymmetry, they often leave operational asymmetry intact (Campbell-Johnston et al., 2021; Joltreau, 2022). Third, they provide quasi-experimental evidence that infrastructure standardisation can induce structural shifts in household disposal behaviour, while highlighting the need for adaptive governance mechanisms to sustain performance over time.

1.1 Background and Policy Context

Waste management in Iceland historically evolved under conditions distinct from continental Europe. Little is documented regarding waste management prior to 1970, though practices predominantly involved open sea dumping, burning, or unregulated landfilling (Meyles, 2003). Between 1970 and 1990, the system transitioned toward controlled open-pit burning and landfilling, supplemented by the construction of three early incineration facilities (Meyles, 2003). Data from this period remains fragmentary, often relying on rough estimates rather than systematic weighing (Meyles, 2006).

Abundant land availability, low population density, and high transport costs contributed to a prolonged reliance on landfilling well into the 21st century (Óskarsson et al., 2022). Municipal systems were heterogeneous, characterised by diverse collection schemes, varying service standards, and financing structures largely dependent on municipal tax revenues rather than transparent user-based or producer-based fees. This fragmentation persisted despite the early existence of the Icelandic Recycling Fund (established in 2002), which historically had a limited scope at the municipal household level. It was not until the recent transition to the circular economy framework that the financial and operational responsibilities of producers were significantly expanded (Umhverfis-, orku- og loftslagsráðuneytið, 2022), formally mandating the Fund's participation in financing municipal kerbside collection (Samtök sveitarfélaga á höfuðborgarsvæðinu, 2023).

The regulatory environment shifted significantly following the European Union's Circular Economy Action Plan and amendments to the Waste Framework Directive (European Commission, 2018, 2020). These reforms imposed uniform recovery and landfill diversion targets across member states and associated EEA countries. In Iceland, this generated a structural misalignment between ambitious supranational targets and territorially differentiated cost structures.

The adoption of Act No. 103/2021 (Hringrásarlögin "The Circular Law," 2023) marked a systemic transformation. Fully implemented in January 2023, the reform mandated the following key changes:

- A mandatory harmonised four-bin collection system for households across all municipalities, targeting paper and cardboard, plastic packaging, biodegradable kitchen waste, and mixed residual waste.
- The expansion of the Extended Producer Responsibility framework into a comprehensive, nationwide system for municipal packaging waste, and
- A restructured financial redistribution model, shifting the primary financial responsibility for packaging recovery from municipalities directly to producers through the pre-existing Icelandic Recycling Fund (Úrvinnslusjóður).

In this thesis, the term general bin refers to the household receptacle for mixed residual waste, that is, the waste remaining after recyclable and biodegradable materials have been placed in dedicated collection fractions.

This reform reallocated the primary financial responsibility for packaging waste from municipalities to producers and standardised household infrastructure across all territories. However, harmonisation does not eliminate geographic heterogeneity. Instead, it creates an empirical setting in which the interaction between institutional uniformity and spatial asymmetry can be examined directly.

1.2 Research Gap and Thesis Structure

The international literature on municipal waste governance has developed along three principal strands, which this thesis seeks to bridge.

First, efficiency and cost studies evaluate municipal performance using frontier techniques. Scholars have extensively used DEA to measure technical efficiency in local government services (Worthington & Dollery, 2001), focusing on the operational environment (Simões et al., 2012) and shared inputs in waste processing (Rogge & De Jaeger, 2012). However, these methodologies often struggle to account for extreme spatial dispersion found in Arctic or island contexts.

Second, economic incentive research examines pricing systems, EPR mechanisms, and unit-based charging schemes. Extensive work has been done on the cost savings and efficiency effects of unit-based pricing (Dijkgraaf & Gradus, 2004) and the institutional choices regarding waste collection (Dijkgraaf & Gradus, 2015). Early empirical evidence from the United States demonstrated that while pricing garbage by the bag can reduce waste volume, it may also lead to a significant increase in waste density as households compact their trash, a phenomenon known as the "Seattle Stomp", and, in some cases, induce illegal disposal (Fullerton & Kinnaman, 1996). This highlights the complexity of using financial levers to drive behavioural shifts, as the expansion of recycling programs is often driven as much by local policy mandates as by market

efficiency (Kinnaman, 2006). Furthermore, comprehensive reviews of econometric studies have found that cost savings from privatisation are not systematic, suggesting that the institutional form of delivery (public vs private) may be less decisive for efficiency than local market conditions and operational constraints (Bel & Warner, 2008). Concurrently, the efficacy of EPR in promoting eco-design and funding infrastructure has been debated, particularly regarding how producers interact with municipal systems (Joltreau, 2022) and the future perspectives of producer responsibility within a circular economy (Campbell-Johnston et al., 2021).

Third, behavioural and infrastructure studies analyse how collection design influences separation behaviour. Research indicates that the physical configuration of collection systems, such as the "distance to bin", is often more decisive than financial incentives alone (Struk, 2017). This is supported by findings that infrastructure investments can have stronger direct effects on household behaviour than weight-based tariffs (Andersson & Stage, 2018). Furthermore, variations in recycling rates are frequently attributed to socioeconomic and demographic factors (Abbott et al., 2011), though these drivers may operate differently in spatially constrained settings.

While these strands provide important insights, they are typically examined independently and predominantly in densely populated or continental settings. Limited empirical work integrates efficiency analysis, institutional financing reform, infrastructure configuration, and spatial asymmetry within a unified framework. Moreover, EPR systems are commonly assessed in terms of financial effectiveness or aggregate recovery rates, but rarely in relation to geographic dispersion or seasonal service populations (Arbulú et al., 2024; Campbell-Johnston et al., 2021).

This thesis addresses this gap by analysing circular governance as a multi-layered system in which geography conditions institutional performance and infrastructure mediates behavioural outcomes. Rather than asking whether a specific policy instrument "works," the research examines under what spatial conditions it works and how its effects are structured by territorial heterogeneity.

To systematically explore these dynamics, the research is guided by four overarching research questions spanning the structural baseline (RQ1), the drivers of recovery under institutional reform (RQ2), the resulting behavioural shifts (RQ3), and the synthesis of these elements into a unified framework (RQ4). The thesis adopts a cumulative design in which each article addresses a specific component of a shared analytical framework, allowing for a stepwise examination of how structural, institutional, and behavioural factors jointly shape waste management outcomes. The research questions are operationalised through three empirical phases comprising four interconnected studies:

- Empirical Phase I: Structural Baseline and Efficiency (Papers I & II). The first phase establishes the structural baseline and evaluates efficiency constraints.

Paper I analyses pre-reform cost asymmetries and landfill dependence, highlighting the challenges of achieving EU targets in a remote context (Óskarsson et al., 2022). Building on this, Paper II evaluates municipal efficiency using Data Envelopment Analysis and tests the explanatory power of geographic and socioeconomic variables on performance (Óskarsson et al., 2025).

- Empirical Phase II: Institutional Reform and Recovery Determinants (Paper III). The second phase evaluates institutional reform and early predictors of recovery under the new regulatory framework. Paper III examines early recovery outcomes under the 2023 Expanded EPR framework, identifying seasonal occupancy and collection configuration as mediating factors through Grey Relational and econometric analysis (Óskarsson, Agnarsson, & Davíðsdóttir, 2026).
- Empirical Phase III: Infrastructure and Behavioural Change (Paper IV). The final phase examines infrastructure standardisation and behavioural change at the household level. Paper IV employs panel Interrupted Time Series analysis to test whether the introduction of mandatory four-bin infrastructure was associated with a structural break in disposal behaviour, offering a longitudinal analysis of residual waste diversion (Óskarsson, Agnarsson, Davíðsdóttir, et al., 2026).

Together, the four articles move from structural constraints (Phase I), through institutional reform (Phase II), to realised behavioural outcomes (Phase III), thereby capturing the full policy transmission mechanism. The final synthesis integrates the findings into an analytical framework for circular governance under spatial constraint.

To clarify the analytical structure of the thesis, Figure 1 presents the conceptual framework guiding the research. The framework conceptualises municipal waste management as a socio-technical system shaped by structural conditions, institutional arrangements, and behavioural responses, rather than as a chronological sequence of the research process. Structural factors such as geography, population density, tourism intensity, and settlement patterns influence the organisation and efficiency of municipal waste management systems. The implementation of the harmonised EPR framework in 2023 represents a major policy intervention affecting the financing and organisation of waste collection. Within this framework, the original empirical papers (I–IV) map directly onto the key analytical components of the system. Specifically, Papers I–II address structural conditions and system performance, Paper III examines institutional and infrastructural mediation, and Paper IV analyses behavioural outcomes. The overarching structural constraints at the top, and the final circular economy outcomes and policy adjustments at the bottom, represent the broader theoretical context and the ultimate synthesis developed in the final chapters of this thesis.

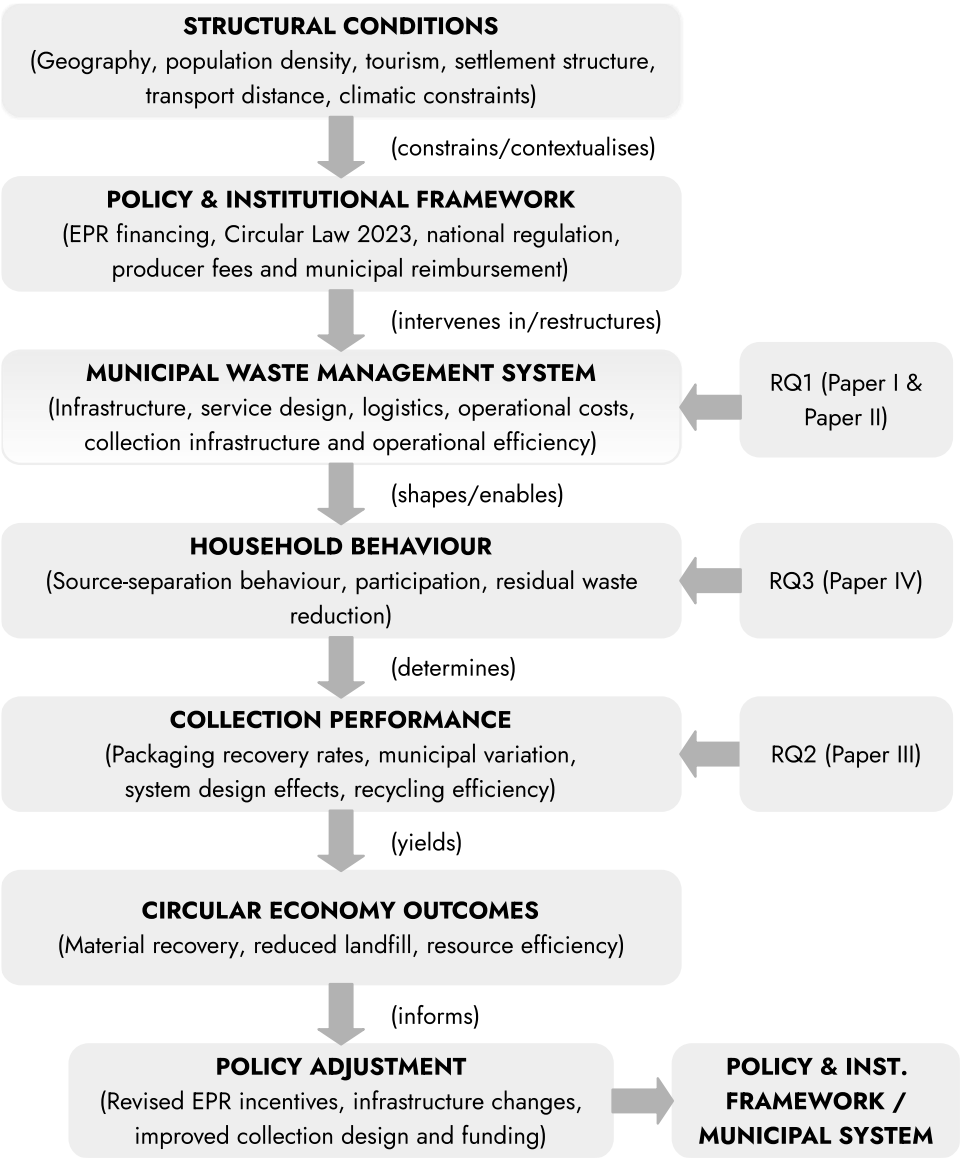


Figure 1. Conceptual framework of municipal waste management as a socio-technical system. The figure presents the analytical structure of the thesis, conceptualising waste management as a multi-level system in which structural conditions condition institutional design, infrastructure configuration, and behavioural responses, thereby shaping system outcomes. The directional relationships should be interpreted as mechanisms of systemic conditioning rather than as a temporal or sequential process. The framework provides the conceptual foundation for integrating the empirical analyses (Papers I–IV) and for the theoretical synthesis developed in the final chapters.

It is important to distinguish between the analytical structure of the system (depicted in Figure 1) and the chronological phases of the research (outlined in Section 4.1 and illustrated in Figure 2). While the phases describe the empirical progression of the thesis, Figure 1 represents a conceptual model of how structural conditions, institutional design, infrastructure configuration, and behavioural responses interact within the waste management system. The directional relationships illustrated in the figure should therefore be interpreted as systemic interactions rather than a temporal sequence.

The 2023 reform establishing a harmonised EPR framework represents a major institutional intervention affecting the financing and organisation of waste collection. The four articles included in the thesis examine different stages of this system: municipal system performance and structural efficiency constraints (Papers I–II), determinants of packaging recovery under EPR (Paper III), and behavioural change following the introduction of harmonised collection infrastructure (Paper IV).

1.3 Thesis Contributions

This thesis contributes to the literature on waste management, environmental policy, and circular economy transitions by providing a system-level analysis of how structural conditions shape the performance of municipal waste management systems under new policy regimes. Using Iceland as an empirical case, the thesis examines how geography, settlement structure, and institutional reform interact to influence recycling outcomes and household waste behaviour.

The thesis makes five main contributions.

First, it provides the first integrated, multi-method analysis of municipal waste management performance in Iceland.

By compiling and analysing previously fragmented municipal data on waste quantities, costs, and treatment outcomes, the thesis establishes a baseline understanding of how Icelandic municipalities perform relative to each other and to international benchmarks. This contributes new empirical evidence to a field where peer-reviewed research on Icelandic waste systems has been limited.

Second, the thesis demonstrates that structural conditions play a central role in explaining variation in municipal waste management performance.

Using Data Envelopment Analysis, the research shows that differences in efficiency across municipalities are strongly associated with factors such as population density, geographic dispersion, and service scale. These findings suggest that observed performance differences are not solely attributable to managerial practices but are strongly influenced by structural constraints characteristic of small and geographically dispersed economies.

Third, the thesis evaluates the early performance of Iceland's EPR reform and identifies key determinants of packaging recovery.

Through the analysis of municipal-level packaging collection data, the research highlights how infrastructure design, spatial characteristics, and service organisation influence recovery rates. The findings emphasise that producer-financed recycling systems interact with local operational conditions, and that infrastructure design can significantly shape the effectiveness of EPR policies.

Fourth, the thesis provides longitudinal evidence of behavioural change following the introduction of harmonised source-separation infrastructure in 2023.

Using panel ITS analysis of municipal waste composition data, the research demonstrates significant reductions in biodegradable material within the residual waste stream following the introduction of the mandatory four-bin system. These findings provide rare empirical evidence on how infrastructure changes can influence household separation behaviour in the short term. Together, these findings indicate that infrastructure is not merely correlated with improved recovery outcomes, but appears to operate as a central household-facing mechanism through which behavioural change is realised, linking system design directly to household-level responses.

Fifth, the thesis synthesises these empirical findings into a four-level analytical framework for circular governance. By mapping how structural geography (Level I) constrains institutional design (Level II) and infrastructure configuration (Level III) to shape realised outcomes (Level IV), the thesis provides a transferable model for evaluating waste governance in other spatially constrained or Arctic economies.

Taken together, this thesis demonstrates that in geographically constrained systems, the effectiveness of circular economy policy is not determined primarily by regulatory ambition or financial incentives alone, but by how these instruments interact with underlying spatial realities and infrastructure configuration. Using Iceland as an empirical case, the findings show that geography defines the feasible efficiency frontier within which municipal systems operate, while institutional reform and infrastructure determine how far systems can move within that frontier. While harmonised instruments such as Extended Producer Responsibility can redistribute financial responsibility, they do not eliminate the structural diseconomies associated with low density and long transport distances.

The central contribution of the thesis is therefore conceptual as well as empirical. By integrating efficiency analysis, institutional reform, and behavioural response within a unified analytical framework, the research advances a system-level understanding of circular governance. In this framework, structural geography functions as a filter mechanism through which policy intent is translated into operational practice and realised outcomes. This perspective shifts the analytical focus from whether circular economy policies "work" in general to the conditions under which they work and how

their effects are distributed across heterogeneous territories. This thesis advances a socio-technical interpretation of circular economy policy in which institutional design operates at a systemic level by shaping incentives and resource flows, while infrastructure operates at the behavioural interface by determining the accessibility and convenience of participation. The findings suggest that policy effectiveness depends less on uniform regulatory design and more on the alignment between institutional frameworks and context-sensitive infrastructure systems.

2 Theoretical Background and Literature Review

This chapter establishes the theoretical basis for analysing municipal waste governance under conditions of spatial asymmetry. While circular economy policy is often presented as a largely technical transition enabled by targets, financing, and improved infrastructure (European Commission, 2020; Geissdoerfer et al., 2017), its implementation depends on how those instruments interact with territorially differentiated cost structures, demographic volatility, and behavioural feasibility. The review therefore develops four theoretical pillars that correspond to the analytical layers of the thesis: (1) spatial economics and the geography of waste systems; (2) institutional design through EPR; (3) municipal performance benchmarking using frontier methods; and (4) behavioural determinants of household source separation, with a focus on the interaction between convenience and incentives. These theoretical pillars are integrated through a socio-technical transition perspective, which conceptualises how structural, institutional, and behavioural elements interact within a unified governance system.

2.1 The Spatial Economics of Circular Economy Implementation

The circular economy is described as a regenerative system that aims to slow, close, and narrow material and energy loops to reduce resource inputs and waste outputs (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017; Kirchherr et al., 2017). Early industrial ecology perspectives emphasised material efficiency and value retention within production systems (Ghisellini et al., 2016; Stahel, 2016), while subsequent scholarship has framed CE as a broader socioeconomic transition that integrates production, consumption, and governance across multiple scales (Murray et al., 2017). At the firm level, this transition requires redesign of products and business models to enable reuse, remanufacturing, and longer product lifetimes (Bocken et al., 2016). At the system level, it requires coordinated institutional and infrastructural transformation to support circular flows.

Operationally, circular economy strategies seek to transform waste streams into secondary raw materials and to embed resource efficiency within consumption systems (Popović & Radivojević, 2022). European policy frameworks have translated these principles into harmonised recycling targets, landfill restrictions, and financing mechanisms intended to stimulate convergence in performance across jurisdictions (European Commission, 2020). Implicit in this regulatory architecture is an assumption of spatial neutrality, that the logistical and economic conditions for material recovery are broadly comparable across territories, an assumption that critical scholarship has

questioned for overlooking the physical, social, and moral frictions embedded in resource recovery systems (Gregson et al., 2015).

The literature on island, remote, and Arctic waste systems challenges this assumption. In geographically dispersed contexts, low population density and long transport distances generate structural diseconomies that fundamentally reshape the cost–benefit calculus of diversion (Keske et al., 2018; Óskarsson et al., 2025; Struk, 2017). Remote communities frequently lack sufficient "critical mass" to justify local treatment facilities, resulting in dependence on distant export markets and elevated per-tonne logistics costs (Keske et al., 2018). Empirical work on Arctic waste governance further demonstrates that infrastructure gaps, harsh climatic conditions, and limited economies of scale constrain the feasibility of circular ambitions, regardless of policy intent (Burns et al., 2021). Under such conditions, landfilling may persist not because of weak environmental commitment, but because of operational feasibility and transport intensity (Eisted & Christensen, 2011; Starostina et al., 2014).

These spatial realities complicate the implementation of harmonised policy instruments such as EPR. Although EPR frameworks are designed to standardise recovery incentives and redistribute financial responsibility, their operational effectiveness can vary substantially across territories with different logistical conditions (Diggle & Walker, 2022). Where producer-financed systems interact with high transport costs and dispersed settlements, uniform regulatory templates may produce uneven outcomes.

Empirical research from rural Europe reinforces this structural perspective. Economies of scale significantly influence municipal waste management costs, and smaller or more dispersed jurisdictions face inherent cost disadvantages independent of managerial performance (Bel & Fageda, 2010; Bel & Mur, 2009; Bel & Warner, 2008). This suggests that the feasible efficiency frontier itself varies across space. When circular economy instruments are implemented uniformly across heterogeneous territories, differentiated results may therefore reflect structural geography rather than institutional failure.

This spatial economics perspective is foundational for the present thesis. If geography defines the operational limits within which circular policies function, then it effectively acts as a filter mechanism; thus, institutional harmonisation cannot be evaluated independently of territorial structure. In the Icelandic context, characterised by import dependence, demographic volatility, and extreme settlement dispersion, these dynamics become particularly visible (Óskarsson et al., 2022). The case thus provides an opportunity to examine how circular economy governance performs when institutional ambition interacts with a binding geographic constraint.

2.2 Extended Producer Responsibility in Heterogeneous Space

Extended Producer Responsibility is widely described as a core instrument for financing and governing post-consumer waste systems by shifting responsibility from municipalities to producers, commonly via Producer Responsibility Organisations (Lifset et al., 2013; OECD, 2016). The concept was originally formalised as a policy principle intended to promote environmental improvements of product systems by extending the producer's responsibility to the post-consumer stage of a product's life cycle (Lindhqvist, 2000). Ghisellini et al. (2016) characterise EPR as an essential policy instrument in the European context, functioning as an economic tool to internalise environmental externalities into product prices while promoting the efficient management of specific material streams. This internalisation also creates a potential channel through which producer fees may be reflected in consumer prices, depending on the extent to which producers absorb or pass on these costs (OECD, 2016; Walls, 2006). In circular economy governance, EPR is expected to (i) provide stable funding for collection and treatment, (ii) reduce fiscal burdens on municipalities, and (iii) create incentives for eco-design and prevention (Joltreau, 2022; OECD, 2016). The core intent of these policies is to internalise end-of-life environmental impacts, thereby providing a clear incentive for producers to reduce waste through upstream design changes (Walls, 2006). The ability of take-back legislation to achieve these environmental targets efficiently is often mediated by factors such as industry structure, product classification, and the willingness of end-users to participate in recovery programs (Atasu et al., 2009). Beyond these logistical factors, the implementation of EPR is not merely a financial transaction; it is a complex governance transition. Kunz et al. (2018) argue that the effectiveness of these systems relies heavily on "institutional embedding", the extent to which stakeholder roles are clearly defined and accepted by all actors. Without broad stakeholder alignment, the redistribution of responsibility can generate friction between producers (who pay) and municipalities (who operate).

This tension becomes especially visible in spatially heterogeneous settings. While EPR can harmonise financial responsibility, it does not automatically harmonise operational performance. Recent empirical work highlights that in jurisdictions with complex logistics or remote territories, there is often a disconnect between the "financial responsibility" assumed by producers and the "operational reality" faced by local governments (Leclerc & Badami, 2024).

In territorially asymmetric systems, collection costs vary across space while producer fees or reimbursement mechanisms may remain relatively uniform. This creates a risk that EPR may reduce fiscal asymmetry (who pays) while leaving operational asymmetry (how costly recovery is) intact. The Icelandic case is therefore theoretically valuable: it enables analysis of how a newly harmonised EPR framework performs when implemented across municipalities facing sharply different spatial cost structures and demographic dynamics. As Ghisellini et al. (2016) emphasise, the ultimate success of

such macro-level instruments depends on their ability to achieve a balanced interplay between environmental and economic systems, effectively decoupling growth from material throughput across all participating territories. Because spatial and operational asymmetries complicate the implementation of harmonised policies like EPR, accurately measuring local performance becomes a critical governance challenge.

2.3 Benchmarking Municipal Performance Under Spatial Constraint

To evaluate whether municipalities perform efficiently, the literature commonly applies frontier methods, such as DEA, to local government services (Worthington & Dollery, 2001). These models allow for the assessment of technical efficiency by comparing multiple inputs and outputs, accounting for shared operational processes in waste collection and treatment (Rogge & De Jaeger, 2012, 2013). The validity of these benchmarks, however, depends entirely on the accuracy of the demographic data used to normalise inputs. While registered resident populations serve as a reliable proxy for waste generation in stable, urbanised contexts, this proxy breaks down in tourism-intensive economies, creating a structural "denominator bias." A critical strand of literature demonstrates that the "service population", the actual aggregate of residents, tourists, and seasonal occupants, diverges substantially from census data, as tourists often generate significantly higher waste volumes per capita than residents due to consumption patterns and limited access to source-separation infrastructure (Arbulú et al., 2024).

Recent empirical evidence from Portugal supports this distortion. Costa et al. (2025) found that in the tourism-intensive Algarve region, per-capita waste generation metrics are systematically inflated by seasonal population surges. Similarly, Mateu-Sbert et al. (2013) demonstrate in the case of Menorca that in island environments, the pressure exerted by floating populations strains infrastructure designed solely for permanent residents, effectively penalising municipalities for the "hidden" waste load of visitors.

In the Icelandic context, where seasonal occupancy intensity, proxied using a metric introduced here as the "cottage ratio" of holiday homes to permanent residences, is substantial, this bias is systematic. Consequently, rural municipalities may appear inefficient in DEA assessments not because of managerial failure, but because they are servicing a population that contributes to cost and volume but not to the statistical denominator (Caponi, 2022; Struk & Boďa, 2022). What is identified as managerial underperformance in standard reporting may, upon closer inspection, represent a structural mismatch between service demand and the permanent resident base, indicating the need to move toward dynamic "service load" models that incorporate tourism intensity and seasonal occupancy into population denominators.

2.4 Behavioural Determinants: Convenience, Infrastructure, and Incentives

Municipal recycling outcomes ultimately depend on household participation. Research on household source separation frequently distinguishes between economic incentives, such as unit-based pricing, and convenience factors, such as collection proximity, accessibility, and system simplicity. Empirical studies show that unit-based pricing can reduce residual waste and shift behaviour, but outcomes also depend on institutional and collection choices (Dijkgraaf & Gradus, 2015, 2004). However, the magnitude of this reduction may be smaller than anticipated if households respond to volume-based fees by merely increasing the density of the waste they present for collection (Fullerton & Kinnaman, 1996).

At the same time, a substantial body of evidence indicates that "distance to bin" and infrastructure accessibility are among the most robust predictors of participation in source separation (Struk, 2017). This is consistent with findings that waste policy instruments often operate through both direct and indirect behavioural pathways and that system design can condition behavioural responses (Andersson & Stage, 2018). Furthermore, the effectiveness of these collection systems is often material-dependent: household separation behaviour varies across packaging formats, with large and conspicuous items separated more consistently than small, lightweight, or contamination-prone plastic packages (Thoden Van Velzen et al., 2019). While kerbside collection is often prioritised for its convenience, recent research emphasises that recycling drop-off centres remain a critical component of the infrastructure, capable of generating significant diversion effects when strategically located (Xirogiannopoulou et al., 2024).

Socioeconomic and demographic correlates also shape household separation behaviour and help explain variation in recycling performance (Abbott et al., 2011). Furthermore, when new infrastructure or policy interventions are introduced, households may initially alter their behaviour simply because the change is new, highly visible, or actively promoted. This short-term reaction reflects a tendency for participation gains to diminish over time, whereby participation may initially increase following system introduction but subsequently decline as the intervention becomes routine. Consequently, early improvements in recycling performance following policy interventions should be interpreted cautiously, particularly when evaluating reforms over relatively short time horizons (Andersson & Stage, 2018; Struk, 2017; Thøgersen, 2003). Recent behavioural evidence further highlights that infrastructure-driven changes may not automatically persist without reinforcement. Systematic reviews of experimental interventions suggest that behavioural responses can depend on design features, feedback mechanisms, and sustained engagement rather than one-time interventions alone (Wilson et al., 2025). This matters for circular economy reforms that rely on rapid

behavioural adaptation following infrastructure rollout: early gains may stabilise unless complemented by additional governance mechanisms.

For this thesis, the behavioural pillar therefore supports two propositions: (i) infrastructure accessibility, whether through kerbside collection or well-designed drop-off systems, is likely to be a primary driver of immediate changes in household separation behaviour; and (ii) long-term performance depends on maintenance mechanisms beyond the initial rollout.

2.5 Socio-Technical Transitions and Policy Translation

The transition toward a circular economy is frequently framed as a normative and largely technical process driven by regulatory targets, financial instruments, and infrastructure investment (Geissdoerfer et al., 2017). However, the implementation of such systemic change in waste governance requires moving beyond technical blueprints to understand the circular economy as a complex socio-technical system (Geels, 2011).

Socio-technical transition theory, particularly the Multi-Level Perspective (MLP), conceptualises systemic change as the interaction between three analytical levels: macro-level "landscapes" (deep structural conditions such as geography and demography), meso-level "regimes" (institutional frameworks, policy instruments, and established governance systems), and micro-level "niches" (local practices, innovations, and behavioural routines) (Geels, 2011). Transitions occur not through linear policy implementation, but through the dynamic interaction and alignment of these levels over time.

While the MLP provides a robust framework for understanding systemic change, economic geographers have increasingly noted that such transitions are not spatially neutral; rather, they are profoundly conditioned by regional and territorial characteristics (Coenen et al., 2012; Gregson et al., 2015). Applied to municipal waste governance, this perspective highlights a fundamental tension: circular economy policies, such as harmonised EPR systems and EU recycling targets, operate primarily at the regime level, seeking to standardise incentives, financing, and performance across jurisdictions. However, their implementation is ultimately conditioned by landscape-level factors, including population density, settlement dispersion, transport distances, and demographic volatility. In geographically dispersed, island, or Arctic contexts, these structural conditions impose significant constraints on the feasibility and cost-efficiency of waste management systems (Eckelman et al., 2014; Keske et al., 2018).

This interaction creates friction between policy intent and operational reality. As Korhonen et al. (2018) argue, the circular economy concept risks remaining normatively attractive but empirically under-specified if it does not account for real-world constraints. Similarly, the public administration literature on policy

implementation emphasises that an "implementation gap" often emerges when uniform policies interact with heterogeneous local capacities and contextual conditions (Hill & Hupe, 2014; Kaplan Weinger, 2026).

To address this gap, policy implementation must be understood as a process of "policy translation" within multi-level governance systems (Kern & Alber, 2008). Rather than being passively adopted, national and supranational policy instruments are actively interpreted, adapted, and operationalised by local actors within the constraints of their specific territorial contexts.

In this thesis, this perspective provides the theoretical foundation for conceptualising municipal waste management as a multi-layered socio-technical system. Structural geography functions as a macro-level constraint that conditions the translation of institutional design into operational infrastructure and behavioural outcomes. This mediating role is conceptualised as a "filter mechanism," through which policy intent is transformed as it moves across levels of the system.

This socio-technical interpretation directly informs the integrated analytical framework developed in Chapter 6. While Geels' (2011) traditional MLP utilises a three-tier structure, this thesis adapts that taxonomy into a four-layered operational model specifically suited for waste governance. In this adapted framework, the MLP "Landscape" aligns with the binding constraints of structural geography, the "Regime" corresponds to the regulatory scaffold of institutional design, and the micro-level interactions are split into two distinct stages: the physical interface of infrastructure configuration and the final realised outcomes of the system.

3 Theoretical Synthesis and Research Aims

3.1 From Theory to Research Design

The theoretical synthesis developed in Chapter 2 provides the conceptual foundation for the empirical analysis undertaken in this thesis. Although supranational circular economy frameworks are often presented as technical transitions enabled by top-down regulatory targets and financial instruments (European Commission, 2020; Geissdoerfer et al., 2017), their operational success is ultimately constrained by ground-level constraints. Real-world implementation depends fundamentally on how these harmonised policies interact with territorially differentiated cost structures, demographic volatility, and behavioural feasibility.

To capture this complexity, the research design integrates four complementary theoretical pillars corresponding to the analytical layers of the thesis. First, spatial economics provides the foundation for evaluating how geographic constraints, such as low population density, settlement dispersion, and transport intensity, shape the feasible efficiency frontier within which municipal waste systems operate. This perspective is operationalised through comparative cost analysis and Data Envelopment Analysis (Rogge & De Jaeger, 2013; Simões et al., 2010, 2012; Worthington & Dollery, 2001), allowing the separation of structural constraints from managerial performance.

Second, institutional design is examined through the lens of Extended Producer Responsibility, focusing on how harmonised financing mechanisms interact with heterogeneous service conditions (Campbell-Johnston et al., 2021; Joltreau, 2022; Lifset et al., 2013; OECD, 2016). Particular attention is given to the role of demographic distortion, especially tourism-driven seasonal occupancy, which introduces systematic measurement challenges in per-capita performance indicators (Arbulú et al., 2024; Caponi, 2022). While EPR schemes are often evaluated in terms of financial incentives and regulatory design, their effectiveness ultimately depends on the physical systems through which households separate their waste, highlighting the critical role of infrastructure as the behavioural interface of policy.

Third, behavioural determinants are analysed through the infrastructure and accessibility literature, which emphasises how collection system design, such as kerbside versus drop-off configurations, influences household separation behaviour (Andersson & Stage, 2018; Dijkgraaf & Gradus, 2015, 2004; Struk, 2017). This perspective also highlights the importance of behavioural sustainability, recognising that initial responses to policy and infrastructure change may not persist without reinforcement (Wilson et al., 2025).

Finally, these strands are integrated into a system-level governance perspective, conceptualising municipal waste management as a multi-level socio-technical system. Rather than viewing policy implementation as a linear process, this thesis proposes that circular economy outcomes emerge through a hierarchical filtering mechanism. Specifically, structural geography (Level I) acts as a binding constraint that conditions the operational realisation of institutional design (Level II). This institutional scaffold, in turn, shapes infrastructure configuration (Level III), which serves as the physical interface through which behavioural responses and system outcomes (Level IV) are realised. By structuring the empirical analysis around these interactions, the thesis builds toward an integrated analytical framework, formalised in Chapter 6, that explains circular governance under spatial asymmetry.

These theoretical pillars are operationalised through a sequential empirical design that moves from structural constraints (Phase I), through institutional reform (Phase II), to behavioural outcomes (Phase III), before being synthesised into an integrated framework for circular governance under spatial asymmetry.

3.2 Overarching Aims

The overarching aim of this thesis is to explain how spatial structure, institutional reform, and infrastructure configuration jointly condition realised outcomes in municipal waste management systems within a geographically dispersed Arctic economy.

In particular, the thesis evaluates whether harmonised circular economy instruments, especially Extended Producer Responsibility (EPR) financing and infrastructure standardisation, can mitigate, rather than eliminate, the spatial diseconomies inherent in low-density territories. By integrating spatial economics, public finance, and socio-technical systems analysis, the research moves beyond descriptive benchmarking to develop a transferable analytical framework for circular governance under conditions of spatial asymmetry.

3.3 Research Questions and Empirical Operationalisation

To achieve these aims, the thesis addresses four core research questions corresponding to the structural baseline, institutional reform, behavioural response, and theoretical synthesis. These macro-level questions are operationalised through specific empirical sub-questions addressed in the constituent papers.

RQ1. The Structural Baseline

To what extent are observed differences in municipal waste management efficiency explained by exogenous socioeconomic and geographic constraints associated with an Arctic context?

Empirical Operationalisation:

This question is addressed in Phase I (Papers I and II), which establishes the structural and financial baseline of Icelandic waste governance.

Sub-question 1.1 examines the baseline trajectory of waste generation and the extent of cost asymmetry across municipalities prior to institutional reform (Paper I).

Sub-question 1.2 evaluates how structural variables, particularly population density and geographic scale, affect technical efficiency when isolated from operational management (Paper II).

RQ2. The Drivers of Recovery

How did the transition to an expanded and harmonised Extended Producer Responsibility (EPR) framework influence material recovery, and how are these effects mediated by seasonal occupancy and collection-system configuration?

Empirical Operationalisation:

This question is addressed in Phase II (Paper III), which evaluates institutional reform and early recovery outcomes under the harmonised EPR framework.

Sub-question 2.1 examines how material-specific apparent recovery rates evolve following the implementation of the 2023 reform.

Sub-question 2.2 investigates the extent to which seasonal occupancy intensity creates denominator bias in per-capita performance metrics.

Sub-question 2.3 evaluates how the balance between kerbside and drop-off collection systems mediates recovery outcomes in low-density environments.

RQ3. The Behavioural Shift

Did the introduction of a mandatory, harmonised four-bin system induce a structural break in household disposal behaviour, particularly in relation to organic waste diversion?

Empirical Operationalisation:

This question is addressed in Phase III (Paper IV), which provides longitudinal evidence of behavioural change following infrastructure standardisation.

Sub-question 3.1 tests whether the introduction of four-bin source-separation infrastructure generated a statistically significant structural break in residual waste composition.

Sub-question 3.2 examines whether behavioural responses differ across material fractions, particularly between biodegradable waste and recyclable materials such as paper and plastic.

RQ4. Synthesis and Policy Design

What integrated analytical framework can explain how structural geography mediates circular governance outcomes under conditions of spatial asymmetry?

Theoretical Operationalisation:

This question is addressed through the synthesis presented in Chapter 6, where the empirical findings are consolidated into a multi-level analytical framework.

The central synthesis question examines how structural conditions, institutional design, and infrastructure configuration interact as a "filter mechanism" shaping realised circular economy outcomes.

3.4 Summary of Research Design Alignment

To explicitly link the empirical progression of this thesis to the conceptual model introduced earlier, Table 1 aligns the core Research Questions (RQs) not only with their respective theoretical frameworks and methods, but also with their specific focus areas within the waste management system (as depicted in Figure 1). While the empirical phases denote the chronological timeline of the research, the target of each phase systematically isolates a distinct level of the four-level socio-technical system, thereby building the evidentiary foundation for the integrated analytical framework developed in Chapter 6.

Table 1. Alignment of Research Questions, Theoretical Frameworks, Methodological Approaches, and System Focus.

Research Phase	Core Research Question	Theoretical Focus	Associated Publication(s) & System Focus	Primary Methodological Approach
Empirical Phase I: Structural Baseline	**RQ1:** Are efficiency differences explained by exogenous geographic constraints?	Spatial Economics & Efficiency Benchmarking	**Papers I & II** System Focus: Structural Conditions & Municipal Waste Management System	Descriptive Statistics, Comparative Cost Analysis, Data Envelopment Analysis (DEA)
Empirical Phase II: Institutional Reform	**RQ2:** How does EPR influence recovery, and how is it mediated by demography and infrastructure?	Public Finance & Institutional Design	**Paper III** System Focus: Policy & Institutional Framework & Collection Performance	Grey Relational Analysis (GRA), Econometric Modelling (Pooled OLS)
Empirical Phase III: Behavioural Shift	**RQ3:** Did the harmonised four-bin system induce a structural break in household separation behaviour?	Behavioural Economics & Infrastructure Configuration	**Paper IV** System Focus: Household Behaviour	Panel Interrupted Time Series (ITS), Segmented Regression
Synthesis: System Integration	**RQ4:** What framework explains how structural geography mediates CE outcomes?	Socio-Technical Systems & Circular Governance	**Kappa (Thesis)** System Focus: System-wide Integration	Integrated Multi-Level Framework Development

This thesis is structured as a cumulative empirical investigation in which each paper addresses a distinct component of a shared analytical framework. Rather than constituting independent studies, the four papers are designed as sequential steps in testing how municipal waste management performance emerges under structural constraints.

Papers I and II establish the structural conditions under which waste systems operate, demonstrating how geographic and demographic factors define the feasible efficiency frontier. Building on this, Paper III examines how institutional reform, specifically the introduction of an extended producer responsibility (EPR) framework, interacts with these structural conditions, identifying key mediating variables such as collection system

design and seasonal population dynamics. Paper IV then isolates the behavioural mechanism through which policy is translated into outcomes, using a longitudinal design to estimate changes in household separation behaviour following the introduction of new collection infrastructure.

Taken together, the four papers form a coherent analytical sequence linking structural conditions, institutional design, operational systems, and behavioural responses to observed recycling outcomes. This cumulative research logic and the analytical positioning of each paper within the framework are summarised in Table 2.

Table 2. Mapping of the Four Papers to the Thesis Analytical Framework.

Paper	Analytical Level	Role in Thesis	Key Contribution
Paper I	Level I: Structural geography	Defines constraint space	Identifies cost and scale diseconomies
Paper II	Level I: Structural efficiency	Tests efficiency under constraints	Demonstrates structural drivers of performance
Paper III	Level II–III: Institutional → operational	Examines policy translation	Identifies mediating factors (collection, seasonality)
Paper IV	Level III–IV: Infrastructure–behaviour interface	Identifies quasi-experimental behavioural response	Estimates structural change in residual waste composition
Thesis synthesis	Level IV: Outcomes + feedback	Integrates system	Explains how outcomes emerge

4 Materials and Methods

This thesis employs an integrated, multi-method quantitative research design combining administrative data analysis, economic modelling, and physical waste characterisation. The empirical scope of this thesis is municipal solid waste and related household and packaging waste streams managed through municipal collection systems. Livestock waste, agricultural residues, animal mortalities, and rendering streams are outside this scope and are not included in the datasets analysed; consequently, they do not influence the reported municipal waste-management results. The methodological architecture reflects the multi-layered analytical framework developed in the thesis, where structural geography, institutional reform, infrastructure configuration, and behavioural response are examined as interdependent components of a socio-technical governance system.

Rather than applying a single methodological approach across all empirical questions, each study employs techniques selected to address a distinct layer of the framework: structural efficiency via Data Envelopment Analysis (Charnes et al., 1978), institutional mediation via Grey Relational Analysis (Deng, 1989), and behavioural change via panel Interrupted Time Series analysis (Lopez Bernal et al., 2016; Wagner et al., 2002).

4.1 Evolution of the Research Design

Although the methodological core of the thesis is quantitative, the empirical environment evolved significantly during the doctoral period. The original research design focused on a broad status assessment of Icelandic waste management, with particular attention to cost-effectiveness and macroeconomic drivers of waste generation, especially the relationship between economic growth (GDP) and municipal waste volumes.

However, the enactment of Act No. 103/2021 (Hringrásarlögin "The Circular Law," 2023) and the implementation of the newly harmonised EPR framework in January 2023 constituted a major institutional intervention. This reform altered financial flows, reporting structures, and household infrastructure across municipalities. Rather than limiting the research to descriptive benchmarking, this policy shift created an opportunity to evaluate circular economy reform in real time within a structurally asymmetric context.

The research design, therefore, evolved through three analytically coherent phases:

Empirical Phase I: Structural Baseline and Efficiency (Papers I & II)

The first phase established the structural and financial baseline of Icelandic waste governance. Initial analyses confirmed the close relationship between economic growth (GDP) and waste generation. However, more consequential findings emerged regarding substantial regional cost disparities. This prompted a transition from descriptive assessment toward frontier efficiency analysis using DEA.

The purpose of the DEA was to distinguish managerial inefficiency from exogenous geographic determinants. By incorporating socioeconomic and spatial variables in second-stage regression analysis, the study evaluated whether performance differences reflected operational shortcomings or structural diseconomies associated with low density and long transport distances.

Empirical Phase II: Institutional Reform and Recovery Determinants (Paper III)

The implementation of the expanded EPR framework introduced new financial incentives and harmonised reporting categories. Given the limited time series available under the new regime, the analytical focus shifted from long-term trend analysis to a cross-sectional evaluation of early recovery outcomes, with the objective of explaining differentiated outcomes under uniform institutional reform.

Empirical Phase III: Infrastructure and Behavioural Change (Paper IV)

The final phase examined whether mandatory infrastructure standardisation induced behavioural change. Panel ITS analysis using segmented regression was applied to longitudinal waste characterisation data. This quasi-experimental approach enabled the identification of structural breaks in disposal behaviour while controlling for pre-existing trends.

Together, these phases reflect analytical adaptation to a dynamic policy environment. The evolution of the research design represents methodological responsiveness to institutional change, allowing the thesis to move beyond static benchmarking toward an integrated evaluation of governance under spatial asymmetry, ultimately capturing the full policy transmission mechanism. To clarify this methodological structure and the evolution across the three empirical phases, Figure 2 summarises the analytical strategy used across the four articles.

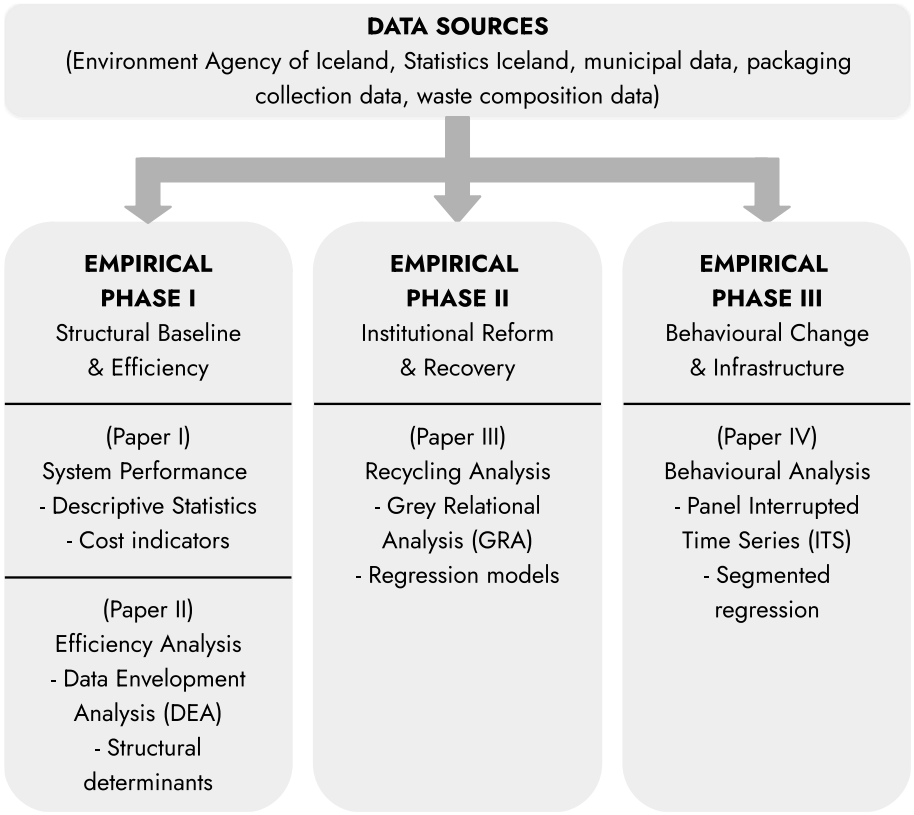


Figure 2. Analytical strategy and multi-method research design. The columns illustrate the chronological timeline of the research across three empirical phases, in contrast to the analytical system structure presented in Figure 1. The methodological approach evolves from establishing the structural baseline (Empirical Phase I), to evaluating institutional reform (Empirical Phase II), and finally to identifying quasi-experimental behavioural change (Empirical Phase III).

4.2 Data Sources

The empirical analyses in this thesis rely on a combination of national registries, municipal accounts, supranational databases, and physical waste characterisation studies. Given the fragmented nature of historical waste data in Iceland, compiling a comprehensive dataset required harmonising information from multiple institutional sources. The primary data sources, mapped across the four constituent papers, include:

- Statistics Iceland (Hagstofa Íslands, https://www.hagstofa.is): Served as the foundational demographic and socioeconomic dataset across all four studies (Papers I–IV). It provided critical data on population counts by municipality, age, and sex, which were essential for normalising waste metrics and establishing per-capita indicators.

- The Environment and Energy Agency (Umhverfis- og orkustofnun, https://uos.is; formerly the Environment Agency of Iceland, Umhverfisstofnun, https://www.ust.is) & Environmental Portals: Provided national data on total waste volumes, treatment methods, and municipal waste indicators. This was a key source for establishing the structural baseline in Paper I and evaluating municipal efficiency in Paper II (utilising the urgangur.is dashboard). Supplementary environmental portal data (gatt.natt.is) was also utilised in Paper III.
- Icelandic Association of Local Authorities (Samband íslenskra sveitarfélaga, https://www.samband.is): Provided comprehensive municipal financial accounts. This database was essential for extracting waste management operational costs, service revenues, and fiscal imbalances, enabling the cost comparisons in Paper I, the efficiency modelling in Paper II, and the per-capita cost assessments in Paper III.
- Eurostat (https://ec.europa.eu/eurostat/data): Utilised in Papers I and II to benchmark Iceland's municipal and packaging waste generation, treatment operations, and landfill rates against EU-27 and other Nordic averages.
- Icelandic Recycling Fund (Úrvinnslusjóður, https://www.urvinnslusjodur.is): Served as the central administrative dataset following the 2023 EPR reform. It provided harmonised, municipal-level data on packaging waste collection (paper and plastic) used in Paper III, and supported the longitudinal recovery tracking in Paper IV.
- SORPA (Capital Region Waste Management, https://www.sorpa.is): The primary data source for Paper IV, providing deep longitudinal data (2014–2025) on residual waste composition. This dataset is derived from systematic physical sorting and weighing of household waste streams. To minimise the confounding effects of seasonal variation, these sampling campaigns were conducted consistently during the autumn months throughout the study period, enabling the quasi-experimental evaluation of behavioural changes.
- Registers Iceland (Fasteignaskrá, https://hms.is/fasteignaskra): Used in Paper III to extract data from the National Property Registry regarding the number of residential properties and holiday homes. This was necessary to calculate the seasonal occupancy intensity (proxied here by the "cottage ratio") to demonstrate denominator bias.
- National Land Survey of Iceland (Landmælingar Íslands, now integrated into Náttúrufræðistofnun, https://www.natt.is/is): Provided spatial and geographic data via the Icelandic Spatial Data Infrastructure (Markasjá). This data was critical for calculating municipal area sizes, population density, and spatial dispersion in Papers II and III.
- Ministry for the Environment, Energy and Climate (Umhverfis-, orku- og loftslagsráðuneyti, https://www.stjornarradid.is/raduneyti/umhverfis-orku-og-loftslagsraduneytid/; formerly Ministry for the Environment and Natural

Resources): Provided policy documentation and foundational strategic data regarding Iceland's transition toward a circular economy, which contextualised the baseline assessment in Paper I.

These datasets collectively enabled a multi-dimensional analysis spanning financial, material, behavioural, and spatial governance dynamics.

4.3 Data Quality and Structural Data Constraints

Data quality is treated not solely as a methodological limitation, but as an empirical indicator of administrative capacity under spatial constraint. The same geographic fragmentation that characterises waste collection in Iceland has historically shaped reporting practices and statistical continuity.

Four dimensions of data constraint are particularly relevant: historical discontinuity, geographic exclusion, metric mismatch, and demographic revision.

4.3.1 Historical Discontinuity

Systematic waste data collection in Iceland did not begin until approximately 1990, and reliable, weighed measurements were not consistently implemented until the early 2000s. The adoption of the European Waste Classification for Statistics (EWC-Stat) in 2014 improved harmonisation; however, long-term comparisons remain sensitive to earlier irregularities.

A further discontinuity occurred with the 2023 reform. Harmonised municipal-level data for specific packaging streams became available only after the implementation of the reformed EPR framework. Consequently, pre- and post-reform comparisons of material-specific recovery rates require distinct analytical strategies: long-term trend analysis for aggregate variables (Papers I and IV) and short-term cross-sectional analysis for specific packaging determinants (Paper III).

4.3.2 Geographic Exclusion and Urban Bias

The extreme spatial dispersion of Iceland generates a structural data exclusion effect. In Paper II, the DEA analysis was restricted to 48 of 69 municipalities due to insufficient financial or waste data in smaller jurisdictions.

Although the excluded municipalities represent a small share of the national population, they account for a substantial share of land area and are among the most geographically remote. As a result, the efficiency analysis likely yields conservative estimates of spatial diseconomies, since the most structurally constrained systems are underrepresented.

Similarly, waste characterisation data in Paper IV contains a temporal gap in 2020 due to COVID-19 restrictions. The panel Interrupted Time Series model was structured to

account for this missing observation while preserving the longitudinal integrity of the pre-intervention trend.

A further structural consideration concerns municipal consolidation during the study period. The number of municipalities in Iceland declined from 69 in 2021 to 62 in 2024 due to voluntary mergers (Samband íslenskra sveitarfélaga, 2025). Because the primary unit of analysis in Papers I–III is the municipality, these mergers potentially affect longitudinal comparability and panel consistency. To preserve analytical coherence, pre-merger data were retained according to the administrative boundaries valid in the respective year of observation. In cases where mergers occurred during the period of analysis, financial and waste data were harmonised to ensure temporal consistency within each study. While the population share affected by mergers is modest relative to national totals, consolidation may slightly influence scale-sensitive measures such as efficiency scores. However, given the dominant effect of spatial dispersion identified in the analysis, these structural adjustments do not materially alter the overall conclusions.

4.3.3 Metric Mismatch: The Service Population Problem

A central empirical constraint addressed in this thesis concerns the distortion created by standard per-capita metrics. Municipal waste indicators are commonly reported on a per-capita basis using registered population as the denominator. However, in regions with significant tourism flows or seasonal housing, the effective service population may differ substantially from the resident population. This can introduce a form of measurement distortion referred to here as denominator bias, whereby waste generation and recycling indicators are systematically inflated or deflated depending on the mismatch between the resident population and the actual population served by waste collection systems. As demonstrated by the Grey Relational Analysis in Paper III, high seasonal occupancy intensity systematically inflates these metrics, conflating tourism load with local behavioural performance. This metric mismatch penalises rural municipalities in benchmarking exercises and underscores the importance of denominator selection in performance evaluation.

4.3.4 Demographic Revision and Statistical Discontinuity

In 2024, Statistics Iceland (Hagstofa Íslands, 2024) revised its population methodology, retroactively adjusting residency counts to better account for foreign nationals and temporary workers. While this improved demographic accuracy, it introduced discontinuity in the per-capita time series.

Earlier analyses (Papers I and II) rely on population data available at the time of publication, whereas Paper III incorporates the revised methodology. Comparisons across periods must therefore consider potential denominator effects when interpreting per-capita changes.

4.4 Methodological Frameworks

Each empirical study in this thesis employs analytical methods aligned with a specific layer of the integrated framework presented in Figure 1. The thesis adopts an integrated, multi-method analytical strategy to examine the distinct dimensions of municipal waste management performance and policy reform. Waste management systems are complex socio-technical systems in which structural conditions, operational efficiency, policy design, and behavioural responses interact. Because no single empirical method can capture all these dimensions simultaneously, the thesis combines several complementary analytical approaches into a unified framework designed to track the policy transmission mechanism from structural constraints to behavioural outcomes.

This cumulative research design ensures that each paper addresses a distinct component of the shared analytical framework. Papers I and II establish the Level I (Structural) conditions, using Data Envelopment Analysis (DEA) to demonstrate how geographic and demographic factors define the feasible efficiency frontier. Building on this, Paper III examines the interaction between Level II (Institutional Design) and Level III (Infrastructure), using Grey Relational Analysis and regression techniques to identify how the Extended Producer Responsibility (EPR) framework and seasonal population dynamics mediate recovery outcomes. Finally, Paper IV examines Level IV system outcomes by focusing on the household behavioural response associated with the introduction of harmonised collection infrastructure. Using a longitudinal panel Interrupted Time Series (ITS) design, it estimates shifts in household separation behaviour following the introduction of harmonised collection infrastructure.

Taken together, this sequential analytical structure traces the causal pathway through which structural constraints shape institutional design, which is translated through infrastructure systems into behavioural responses and, ultimately, observed recycling outcomes. Descriptive system analysis establishes the baseline, DEA evaluates relative efficiency under spatial pressure, and econometric and quasi-experimental methods assess the impact of reform. Together, these methods provide a comprehensive analytical framework capable of distinguishing between managerial performance and structural limitations in Iceland's municipal waste management system.

4.4.1 Comparative Cost Analysis (Paper I)

Descriptive statistics and trend analysis were used to examine cost structures, landfill dependence, and fiscal imbalances across municipalities. This established the structural baseline against which subsequent efficiency measures were evaluated. The analysis focuses on calculating total waste management expenditures per capita, following standard accounting practices for municipal service evaluation (Óskarsson et al., 2022).

4.4.2 Data Envelopment Analysis (Paper II)

To address RQ1, municipal performance was evaluated using DEA, a non-parametric frontier method originally developed by Charnes et al. (1978) to assess the relative efficiency of decision-making units (DMUs) with multiple inputs and outputs. DEA constructs an empirical production frontier and measures each unit's efficiency relative to the best-performing observations without imposing a pre-specified functional form. This flexibility makes DEA particularly suitable for public-sector applications, where output pricing is often unavailable, and production relationships are complex (Worthington & Dollery, 2001).

Both input- and output-oriented models were employed. The input-oriented specification reflects the assumption that municipalities aim to minimise operational inputs and costs for a given level of service provision. Conversely, the output-oriented model was utilised to assess how effectively municipalities maximise their service outputs, such as material recovery and diversion rates, given their existing structural and financial resources. Variable Returns to Scale (VRS) specifications (Banker et al., 1984) were adopted to account for scale heterogeneity across municipalities, an essential consideration in geographically dispersed systems where economies and diseconomies of scale may coexist.

To examine whether observed efficiency differences reflected managerial performance or exogenous structural conditions, a second-stage regression analysis was conducted using contextual variables such as population density, geographic size, and socioeconomic characteristics. The use of two-stage DEA has been subject to methodological debate, particularly concerning potential bias and serial correlation in estimated efficiency scores (Simar & Wilson, 2007, 2011). While bootstrap procedures have been proposed to address these concerns, the present analysis follows a conventional two-stage framework widely applied in local government efficiency studies (Narbón-Perpiñá & De Witte, 2018a, 2018b). In this thesis, second-stage results are interpreted as identifying structural associations rather than causal effects, thereby reducing the risk of overinterpretation.

This approach enables separation of managerial inefficiency from spatial and demographic constraints that lie outside municipal control (Simões et al., 2012). By explicitly modelling contextual variables, the analysis tests the "spatial penalty" hypothesis that low density and geographic dispersion shift municipalities away from the efficiency frontier independently of managerial capability.

4.4.3 Grey Relational Analysis and Econometrics (Paper III)

To address RQ2, the thesis evaluates early recovery outcomes under the 2023 EPR reform using Grey Relational Analysis (GRA) complemented by econometric modelling. Given the short post-reform time horizon and the relatively small municipal sample

typical of Icelandic datasets, conventional large-sample statistical approaches are limited in explanatory power. Grey System Theory, originally developed by Deng (1989), is specifically designed for systems characterised by "small samples and poor information," where data are incomplete, uncertain, or structurally constrained (Liu, 2025). Unlike conventional statistical frameworks that rely on large-sample asymptotics, grey methods operate under partial information conditions, making them suitable for small and heterogeneous datasets typical of municipal-level sustainability analysis.

GRA assesses the strength of association between a reference sequence (e.g., material recovery rates) and comparative sequences (e.g., seasonal occupancy and collection configuration) by measuring geometric similarity in normalised data patterns. Unlike classical regression models, GRA does not impose strict distributional assumptions and is robust in contexts where sample size and data completeness are limited. Its application in sustainability and environmental research has expanded in recent years, particularly in contexts characterised by data constraints (Javanmardi et al., 2020).

In this thesis, GRA is employed as an exploratory ranking tool to identify the relative importance of structural and infrastructural factors influencing recovery performance. To complement this non-parametric assessment, Pooled Ordinary Least Squares (OLS) estimation (Wooldridge, 2020) was used to test the statistical significance of selected mediating variables, specifically seasonal occupancy intensity (proxied here by the "cottage ratio" of holiday homes to permanent residences) and the relative share of drop-off versus kerbside collection. The use of pooled OLS to evaluate solid waste management outcomes is consistent with recent applied precedents in the literature (Ella et al., 2022). This combined approach enhances analytical robustness by integrating pattern-based association analysis with inferential statistical testing.

Importantly, findings from both GRA and OLS are interpreted as identifying structural associations rather than causal effects. The objective is not to estimate policy impact directly, but to explain differentiated recovery outcomes under uniform institutional reform within a spatially heterogeneous system.

4.4.4 Panel Interrupted Time Series Analysis (Paper IV)

Building on the findings of Paper III, which identified infrastructure configuration as a key determinant of recovery performance, this analysis shifts the focus from system-level outcomes to behavioural response. While improved infrastructure increases the capacity for material diversion, it remains an open empirical question whether such changes translate into actual modifications in household disposal behaviour. Because increased collection volumes may simply reflect expanded system capacity rather than behavioural adaptation, the introduction of the mandatory four-bin source-separation system in 2023 provides a unique opportunity to examine this behavioural dimension within a quasi-experimental framework.

Because the four-bin source-separation system was rolled out across the Capital Region between mid-May and mid-September 2023, that year was treated as a transition year. Annual waste-composition estimates for 2023 combine pre-implementation conditions, estimated using the previous year's composition shares, with post-implementation conditions observed in the autumn 2023 characterisation study. By contrast, 2024 and 2025 represent the first two full years of operation under the harmonised collection system.

To address RQ3, the thesis employs a panel ITS design to evaluate behavioural change following the introduction of the mandatory four-bin system in 2023. ITS is widely regarded as one of the strongest quasi-experimental approaches for evaluating the longitudinal effects of policy interventions when randomised control trials are not feasible (Lopez Bernal et al., 2016; Wagner et al., 2002). By exploiting temporal variation before and after a clearly defined intervention point, ITS enables estimation of both immediate and trend-based changes associated with institutional reform.

The empirical implementation follows a segmented panel regression framework applied to longitudinal waste characterisation data from five analytical areas observed between 2014 and 2025. Structuring the data as a spatial panel increases the effective number of observations and allows control for time-invariant differences between analytical areas through fixed effects. The model estimates three key parameters: (i) the pre-intervention trend, (ii) the immediate level change at the intervention point, and (iii) the post-intervention slope change following the reform. Such segmented regression models allow structural breaks in behaviour to be identified while controlling for underlying secular trends (Linden, 2015; Lopez Bernal et al., 2016).

Panel estimation further improves statistical robustness by accounting for unobserved heterogeneity across analytical areas and exploiting both temporal and cross-sectional variation in the dataset (Wooldridge, 2020). This design, therefore, extends conventional single-series ITS approaches by incorporating spatial variation while retaining the quasi-experimental logic of the intervention analysis.

The analysis is applied to residual waste composition data obtained through the manual sorting and weighing of residual household waste samples. Given the absence of a comparable untreated control group and the national scope of the reform, the ITS framework provides the most rigorous available design for evaluating behavioural response under real-world conditions. Results are interpreted as identifying structural breaks in disposal behaviour rather than causal effects in a strict experimental sense, consistent with best-practice guidance for applied ITS analysis (Linden, 2015; Lopez Bernal et al., 2016).

Collectively, the empirical approaches employed in this thesis, spanning efficiency benchmarking, institutional analysis, and behavioural time-series evaluation, provide a

coherent evidentiary foundation for constructing the integrated socio-technical framework developed in Chapter 6, thereby enabling a system-level response to RQ4.

4.4.5 Software and Implementation

Statistical analyses in this thesis were conducted primarily using R (R Foundation for Statistical Computing, n.d.), supplemented by Stata 16.1 (StataCorp, 2023) for selected procedures in Paper II. Data Envelopment Analysis, econometric modelling, and segmented regression analyses were implemented using established statistical and time-series procedures within the R environment, including specialised packages for efficiency and panel-data analysis. In Paper II, Stata was additionally used for second-stage regression analysis, variance inflation factor (VIF) diagnostics, and correlation coefficient estimation. The use of these platforms ensured analytical transparency, reproducibility, and flexibility in handling panel and longitudinal data structures.

Microsoft Excel was used extensively for initial data cleaning, harmonisation of municipal financial and waste datasets, verification of aggregation procedures, and preliminary descriptive analysis. Excel was also used for the implementation of Grey Relational Analysis in Paper III. Given the heterogeneity of administrative data sources and historical reporting formats, spreadsheet-based validation procedures were employed to ensure consistency prior to statistical modelling.

The combined use of spreadsheet-based preprocessing and statistical software reflects the multi-source nature of the data and supports robustness in both data preparation and model estimation.

5 Results

Drawing on the integrated, multi-method approach outlined in Chapter 4, the results demonstrate how structural geography, institutional reform, and infrastructure configuration jointly shape the realised outcomes of municipal waste management in Iceland. By progressing through the empirical phases, these findings collectively map the full policy transmission mechanism.

5.1 Paper I: Structural Baseline and Cost Asymmetry

Paper I establishes the structural baseline of the system by analysing pre-reform cost asymmetries and landfill dependence, highlighting the challenges of achieving EU targets in a remote context. Initial findings confirmed that municipal waste generation closely tracked macroeconomic drivers, specifically GDP and population size. Furthermore, prior to the 2023 reform, Iceland's landfill rate exceeded 60%, compared to an EU-27 average of approximately 24% in 2020. This positioned Iceland among the most landfill-dependent systems in Europe.

The financial analysis revealed substantial spatial inequality in service costs. Municipalities with fewer than 1,000 inhabitants exhibited per capita waste management expenditures of approximately €379, compared to €106 in municipalities with more than 10,000 inhabitants. This near fourfold difference demonstrates pronounced diseconomies of scale associated with low population density and long transport distances.

These findings confirm that geographic dispersion constitutes a primary structural determinant of cost asymmetry.

5.2 Paper II: Efficiency under Spatial Constraint

Building on the structural cost conditions identified in Paper I, Paper II examines how these constraints translate into observed efficiency differences using Data Envelopment Analysis to test the explanatory power of geographic and socioeconomic variables on performance. Results showed that larger municipalities consistently achieved higher technical efficiency scores.

However, second-stage regression analysis revealed that efficiency variation was significantly associated with structural variables. Population size exhibited a positive and statistically significant relationship with efficiency, while geographic size was negatively associated with performance. Once spatial and demographic variables were

controlled for, much of the observed "inefficiency" in rural municipalities could be attributed to exogenous conditions rather than managerial underperformance.

These findings directly address RQ1 by demonstrating that structural geography materially conditions the efficiency frontier within which municipalities operate.

5.3 Paper III: Institutional Reform and Mediated Realised Outcomes

Having established the role of structural constraints, Paper III shifts focus to the institutional level by examining early realised recovery outcomes under the expanded and harmonised 2023 EPR reform. This study identifies how the reform interacts with local conditions and highlights key mediating variables such as collection system design and seasonal population dynamics.

Material-specific trajectories diverged. Paper packaging apparent recovery increased significantly in 2024, indicating rapid institutional adaptation under producer-funded financing. Plastic apparent recovery, in contrast, remained largely unchanged, suggesting material-specific barriers to capture.

Grey Relational Analysis identified seasonal occupancy as the most influential structural determinant of per-capita recovery performance. Municipalities with high "cottage ratios" exhibited inflated per-capita waste generation metrics, confirming a denominator bias when registered population is used as the sole reference.

In addition, municipalities with a higher share of drop-off collection relative to kerbside collection achieved higher per-capita yields in low-density contexts. This finding challenges the assumption that kerbside collection is universally superior and highlights the mediating role of infrastructure configuration.

These results address RQ2 by demonstrating that recovery performance under harmonised financing is mediated by both demographic structure and system design.

5.4 Paper IV: Infrastructure Standardisation and Behavioural Change

While Paper III identifies the mediating role of system design, Paper IV examines the behavioural mechanism through which infrastructure changes translate into realised outcomes, using a longitudinal panel Interrupted Time Series design to estimate changes in household separation behaviour. The analysis identified a statistically significant structural break in residual waste composition following the 2023 rollout. Total waste in the general bin declined by 37% in the post-reform period, while biodegradable material remaining in the residual stream fell by 54%, indicating that the strongest behavioural response occurred in organic-waste diversion. These findings

provide quasi-experimental evidence that improved infrastructure accessibility was associated with rapid changes in household separation behaviour.

The collection-channel analysis provides further evidence of material-specific performance. Total apparent capture rates in 2024 were 56% for biodegradable waste, 83% for paper, and 44% for plastic, moderating to 53%, 81%, and 41%, respectively, in 2025. Importantly, the high apparent capture of paper reflected the combined contribution of kerbside and drop-off collection. Drop-off containers and recycling centres accounted for approximately 30–34% of the estimated paper quantity throughout 2023–2025, demonstrating that these facilities continued to perform a substantial complementary role following the introduction of harmonised kerbside collection.

The results also indicate that the reform effect was material-specific. The sharpest and most immediate shift occurred in biodegradable waste, consistent with the introduction of dedicated household organic-waste collection. By contrast, the interrupted time-series models indicate that reductions in paper and plastic remaining in the general bin largely reflected the continuation and reinforcement of pre-existing downward trends rather than the emergence of entirely new household separation patterns. These trends may also reflect structural and material changes, including declining printed-paper use and packaging lightweighting. Early data from 2025 suggest an initial stabilisation following the implementation period, consistent with the possibility that initial participation gains may moderate over time and indicating that infrastructure-led improvements require continued behavioural reinforcement.

These results address RQ3 by demonstrating that infrastructure standardisation was associated with measurable structural change in household disposal behaviour, particularly in relation to organic waste. Collectively, these behavioural shifts, alongside the efficiency and recovery outcomes identified through the multi-method analyses in Papers I–III, constitute the realised outcomes of the system. How this policy-transmission mechanism is filtered by spatial and structural constraints is examined in the following discussion and formalised in the integrated analytical framework.

6 Discussion

This chapter interprets the empirical findings of the thesis in relation to the international literature on circular economy governance and municipal waste management. The discussion highlights a central tension revealed by the Icelandic case: circular economy policy instruments are typically designed as spatially neutral mechanisms intended to produce convergence, yet their realised effects are conditioned by territorially differentiated cost structures, demographic volatility, and infrastructure feasibility. The findings therefore support a governance interpretation in which institutional harmonisation can alter incentives and redistribute financial responsibility, but cannot on its own neutralise the spatial diseconomies embedded in low-density systems. Instead, the findings indicate that policy outcomes are filtered through the interaction between institutional design, infrastructure configuration, and underlying spatial conditions.

6.1 Spatial Asymmetry and the Efficiency Frontier

A recurring assumption in supranational waste policy is that harmonised targets and regulatory frameworks will drive convergence in performance across jurisdictions (European Commission, 2020; UNEP, 2011). In practice, this assumes that the operational conditions for compliance are sufficiently comparable. The Icelandic evidence challenges this premise by showing that geography acts not as a contextual nuance but as a binding constraint that conditions the feasible efficiency frontier.

Paper I demonstrated that pre-reform waste governance in Iceland was characterised by pronounced cost asymmetry across municipalities. The severe cost disparities between the smallest and largest municipalities, identified in Paper I, indicate that scale and spatial dispersion are not marginal influences but primary structural drivers of service cost. Similar patterns have been documented in Galicia, where significant economies of scale were found in municipalities with fewer than 50,000 inhabitants, indicating that small jurisdictions face inherent cost disadvantages regardless of managerial performance (Bel & Fageda, 2010). These findings reinforce the Icelandic evidence that geographic size and dispersion act as a structural penalty on technical efficiency (Bel & Mur, 2009). Comparable patterns have been documented in other remote and sparsely populated jurisdictions, including Greenland and northern rural regions where long transport distances and limited economies of scale raise unit costs regardless of local managerial choices (Eisted & Christensen, 2011; Keske et al., 2018). The Icelandic findings extend this insight by quantifying the magnitude of cost divergence within a single regulatory system.

These cost patterns also have direct implications for how municipal performance is evaluated. Efficiency research in local government often applies frontier approaches to benchmark technical performance (Rogge & De Jaeger, 2012; Simões et al., 2012; Worthington & Dollery, 2001). However, benchmarking exercises can misattribute structurally induced high unit costs to managerial inefficiency if spatial conditions are not explicitly modelled. Paper II addressed this problem by separating structural determinants from managerial performance. The positive association between population size and efficiency, combined with the negative association between geographic scale and performance, indicates that a substantial share of observed "inefficiency" reflects exogenous spatial conditions. In this sense, geographic dispersion functions as a structural penalty that shifts municipalities away from the frontier even when operations are competently managed.

This challenge of accurately benchmarking performance is further compounded by the role of seasonal demographics. By failing to account for the "service population," current reporting frameworks systematically underestimate the efficiency of municipalities in high-tourism regions, mistaking structural demographic pressure for operational failure. Furthermore, the strong positive association between the cottage ratio and per-capita material recovery observed in Paper III is consistent with the presence of denominator bias, whereby municipalities with high seasonal occupancy appear to perform better when measured per registered resident. This suggests that observed performance differences may partly reflect measurement artefacts, whereby a small resident base is credited with the recycling efforts of a much larger seasonal population, rather than purely behavioural or system-level differences. Denominator bias operates as a distortion between Level I (structural conditions) and Level IV (observed outcomes), affecting how performance is interpreted rather than how it is generated. In tourism-intensive systems, what appears to be superior performance may partly be a function of how performance is measured rather than how waste is managed. Consequently, the "feasible frontier" of a waste system is as much a matter of statistical definition as it is of operational capacity.

The broader implication is that policy evaluation frameworks that rely on uniform benchmarks risk producing inequitable assessments. In low-density territories, the frontier itself is shaped by geography. Performance comparisons, therefore, require explicit adjustment for spatial conditions if they are to distinguish managerial underperformance from structural limitation.

6.2 Institutional Harmonisation and the Limits of EPR

While structural geography conditions the baseline efficiency constraints of a waste management system, institutional design seeks to standardise how that system is funded and organised. In Iceland, the 2023 reform represented a major institutional shift to address these challenges: primary financial responsibility for packaging recovery

shifted from municipalities towards producers through an expanded Extended Producer Responsibility framework, aligned with broader European circular economy governance (European Commission, 2018, 2020). In principle, EPR can reduce fiscal asymmetry by shifting financing from local tax bases to producer-funded systems and by creating more stable funding for collection and recovery infrastructure. The literature emphasises these functions while debating the extent to which EPR also incentivises upstream prevention and eco-design (Campbell-Johnston et al., 2021; Joltreau, 2022).

This redistribution of financial responsibility may also have implications beyond the municipal waste system, since producer fees can potentially affect production costs and consumer prices. These effects are not examined empirically in this thesis, which does not contain producer-level cost data, product-price data, or a macroeconomic model capable of estimating effects on GDP. Accordingly, the analysis cannot determine whether the expanded EPR framework increased consumer prices or produced measurable macroeconomic effects. Similarly, although the reform altered the financing of municipal collection and required new source-separation infrastructure, the thesis does not estimate the net change in municipal expenditure or infrastructure costs attributable to the EPR reform. The empirical focus is instead on how the reform altered financing arrangements, recovery performance, infrastructure configuration, and household-level outcomes.

The Icelandic waste-management system reflects a multi-level governance structure. At the national level, legislation enacted by Alþingi and policy and regulation administered by the Ministry of the Environment, Energy and Climate establish the overarching framework, including the obligations introduced by Act No. 103/2021. The Environment and Energy Agency (Umhverfis- og orkustofnun) performs national regulatory and supervisory functions and contributes to waste-related data collection and reporting. Producer responsibility is administered through the state-owned Icelandic Recycling Fund (Úrvinnslusjóður), which manages producer fees and their allocation to the collection and recovery of packaging waste. Municipalities retain responsibility for organising household collection, operating or contracting collection services and recycling centres, and setting household waste fees; many fulfil these responsibilities through intermunicipal cooperation. Local health inspectorates also perform licensing and supervisory functions for relevant waste activities. The system is therefore neither fully centralised nor fully municipal: regulatory objectives and important financing mechanisms are established nationally, while operational delivery is organised locally. It is at this interface that the structural constraints identified in Papers I–III shape how common obligations are translated into practice.

The Icelandic findings support the interpretation of EPR as a redistributive financial scaffold, but also demonstrate its limitations in structurally heterogeneous space. Paper III revealed that harmonised financing did not produce uniform recovery outcomes across municipalities. Instead, performance variation persisted and was strongly

mediated by structural and demographic factors. Most importantly, the "cottage ratio" emerged as a primary predictor of apparent per-capita yields, indicating systematic denominator bias when the registered population is used as the benchmark. Differences in municipal recycling performance may partly reflect denominator bias arising from tourism flows and seasonal housing patterns rather than purely differences in household separation behaviour or system performance. This aligns with research on tourism-intensive waste systems, which shows that seasonal population inflows distort municipal waste generation and complicate the interpretation of per-capita indicators (Arbulú et al., 2024; Caponi, 2022).

This finding carries two implications for EPR evaluation. First, EPR may improve funding stability without resolving the measurement problem: performance indicators may still misrepresent municipal "success" or "failure" if the service population differs substantially from the registered population. Second, harmonised funding may remain distributively uneven if reimbursement formulas do not reflect the demographic realities that drive service demand. In low-density territories with substantial seasonal loads, institutional harmonisation can therefore reduce one form of asymmetry (fiscal) while leaving another intact (operational and metric asymmetry).

Crucially, the identification of denominator bias in Phase II (Paper III) provides a vital methodological lens for interpreting the efficiency scores calculated in Phase I (Paper II). It is therefore necessary to disentangle the physical constraints of geography from the statistical distortions of demography.

Rural municipalities in Iceland face a compounding "double penalty." First, they experience genuine operational diseconomies, which this thesis terms spatial friction. Low population density, rugged terrain, and long transport distances inherently require greater inputs (time, fuel, and infrastructure) to service dispersed settlements, creating a structural cost disadvantage and lowering measured efficiency. Second, they face a statistical penalty in the form of denominator bias. This is because the DEA in Paper II relied on registered resident populations to normalise inputs and outputs and thus did not account for the unmeasured service load associated with seasonal tourism and holiday homes.

As a result, the observed inefficiency in rural municipalities reflects a combination of physical and statistical effects. It captures both the material costs of operating in a geographically constrained environment and the distortion introduced by an unobserved service population (Arbulú et al., 2024; Caponi, 2022). Taken together, the findings of the two papers suggest that adjusting the population denominator would alter the measured efficiency gap, although the magnitude of that adjustment cannot be quantified with the available data. Structural geography and demographic volatility therefore appear to jointly shape observed municipal performance.

This gap between policy implementation and realised change is also observed in product design; as Walls (2006) argues, many EPR policies lack the necessary strength to drive significant shifts in "Design for Environment" across complex global supply chains. Bocken et al. (2016) emphasise that these design changes must be supported by circular business model strategies, such as moving from product ownership to service-based models, to effectively slow and close resource loops in practice. This supports the argument that the "right" policy design must account for industry-specific conditions and end-user behaviour to avoid placing an undue economic burden on firms while failing to reach primary environmental targets (Atasu et al., 2009).

The Icelandic case thus contributes to the EPR literature by highlighting that institutional design is filtered through spatial and demographic structure. This does not negate the value of EPR; rather, it clarifies that EPR effectiveness depends not only on producer obligations but also on the alignment between funding formulas, performance metrics, and local service conditions.

Taken together, these findings reinforce a central insight of this thesis: while institutional reform and infrastructure standardisation can be associated with measurable behavioural change, the translation of policy into realised outcomes remains systematically conditioned by spatial structure. By supporting the interpretation of infrastructure as a central operational interface for behaviour, while also showing that this interface remains subject to geographic friction, the analysis highlights the need for a multi-level perspective. This interaction between structural constraints (Level I), institutional design (Level II), and the operational/behavioural interface (Level III) forms the basis for the integrated analytical framework developed in Section 6.4.

6.3 Infrastructure Configuration and Behavioural Response

Yet institutional design and harmonised financing do not, in themselves, translate into material recovery; they must be operationalised through systems that shape how households interact with waste. In short, policy sets the rules of the system, but infrastructure strongly shapes whether and how those rules are followed.

In examining how these systems are utilised, debates about recycling behaviour frequently contrast financial incentives (such as unit-based pricing) with convenience and infrastructure accessibility (Abbott et al., 2011; Dijkgraaf & Gradus, 2015, 2004). Evidence from infrastructure research suggests that "distance to bin" and system design can be decisive drivers of household separation behaviour (Struk, 2017), and that policy instruments often operate through both direct and indirect behavioural pathways (Andersson & Stage, 2018).

The findings of this thesis reinforce this perspective by demonstrating that the effectiveness of the EPR framework is contingent on the configuration of collection

infrastructure, which appears to act as a central transmission pathway through which policy intent is translated into observable behavioural change and recycling outcomes.

Paper IV provides strong evidence of rapid behavioural change associated with infrastructure standardisation, with the clearest response observed for organic waste. The observed structural break in residual waste composition following the four-bin rollout, together with the large reduction in biodegradable material remaining in the residual stream, indicates that households respond strongly when infrastructure reduces convenience barriers for fractions that are highly sensitive to convenience and hygiene. Crucially, the methodological design of Paper IV resolves a central behavioural uncertainty introduced earlier in this thesis: the risk of the "Seattle Stomp" (Fullerton & Kinnaman, 1996). Because the panel ITS analysis relies on systematic physical waste characterisation, specifically the manual sorting and weighing of residual-waste samples rather than the measurement of bin volume, the results circumvent this density distortion. The observed 54% reduction in biodegradable material within the residual stream is therefore not an artefact of spatial compaction, but a confirmed material shift. This supports the interpretation that the harmonised four-bin infrastructure was associated with a substantial change in household source-separation behaviour, diverting biodegradable material away from the general disposal stream. However, while this confirms diversion from the residual bin, verifying absolute circular recovery would require corresponding compositional analysis of the separately collected organic fraction to ensure that diverted material is not merely displaced as contamination into other streams.

Home composting is permitted within Icelandic municipal waste-management arrangements, including in urban as well as rural areas, although its use depends on the rules adopted by individual municipalities (Samband íslenskra sveitarfélaga, 2022). Home composting was not measured directly in this thesis and its contribution to the observed reduction in biodegradable material in the general bin cannot therefore be isolated. Household compliance with the four-bin system is enforced primarily through collection practice rather than monetary fines; for example, Reykjavík City states that bins containing incorrectly sorted waste will not be emptied until the sorting issue has been corrected (Reykjavíkurborg, 2026).

In contrast, the evidence for paper and plastic is more mixed: these fractions improved under the reformed system, but part of their post-2023 pattern appears to reflect the continuation or reinforcement of earlier trends rather than a uniformly discrete behavioural break. This supports a broader economic argument that the rapid expansion of residential recycling over the past decades has been largely driven by the availability of municipal kerbside programs rather than by fluctuating market prices for recycled materials (Kinnaman, 2006), and the interpretation that infrastructure functions as an operational interface through which institutional reform becomes behaviourally actionable. The result is consistent with findings that accessibility and system design can

have stronger immediate effects on separation behaviour than pricing instruments alone (Andersson & Stage, 2018; Struk, 2017). The immediate behavioural response to the organic bin rollout (Paper IV) suggests that infrastructure does not just provide convenience; it operationalises what Stahel (2016) defines as a shift in economic logic toward sufficiency. By making organic diversion a baseline expectation, the reform transitioned households from passive consumers into active stewards of biological nutrients, prioritising the preservation of material value over simple disposal. However, early evidence from 2025 suggests a slight decline following the initial post-reform peak. This moderation of infrastructure-led gains is consistent with the diminishing compliance described in the behavioural literature, whereby participation peaks shortly after system introduction and subsequently moderates as the policy becomes routine. While the quantitative waste composition data robustly confirm this initial levelling off, it cannot illuminate the underlying psychological or practical drivers of this behavioural fatigue. Whether this early stabilisation stems from confusion over specific material contamination guidelines, physical space constraints for four distinct bins within smaller dwellings, or simple routine fatigue remains an unobserved qualitative dynamic in the current data.

Furthermore, the long-term stabilisation of these behavioural shifts depends heavily on public trust in the system's end-of-life processing (Thøgersen, 2003). As highlighted in public discourse during the rollout of the four-bin system, when households perceive that separately collected fractions, such as a significant portion of plastics, are ultimately destined for incineration rather than material recovery, this perception can severely undermine their motivation to participate in source separation (Alexandersson, 2023; Magnúsdóttir, 2023). Historically, local infrastructure like gas collection at Álfsnes and the GAJA facility (SORPA, 2023) provided a tangible, localised narrative for organic recycling that households could understand and trust. If the final disposal method appears to contradict the circular intent of the four-bin system, it risks generating profound "behavioural fatigue" (Wilson et al., 2025). Households may be reluctant to sustain the daily effort involved in source separation if the perceived ultimate outcome is mere disposal, which may partially explain why early infrastructure-led gains risk plateauing over time. Consequently, early performance improvements may not fully persist without continued behavioural reinforcement that specifically targets these human-scale frictions. This highlights a risk identified by Korhonen et al. (2018): all economic efficiency increases are subject to rebound effects and Jevons' paradox, where initial environmental gains from better resource use are offset by overall growth in consumption. Even if the four-bin system improves household source-separation performance, the long-term success of the Circular Law depends on ensuring that these gains are not neutralised by increasing total waste volumes.

It is important to note that the longitudinal waste characterisation data confirming this structural break are drawn from the Capital Region, Iceland's most densely populated area. In the context of the integrated framework, these urban data provide a useful low-

friction baseline, showing that the harmonised four-bin infrastructure was associated with substantial behavioural change under conditions where spatial constraints (Level I) are comparatively limited. However, the magnitude of this behavioural shift cannot be directly extrapolated to remote municipalities. Given the spatial and logistical frictions identified in rural areas (Papers I and II), the findings suggest that the behavioural response to the four-bin system in dispersed settlements is likely mediated by local infrastructural conditions, such as reduced collection frequency or reliance on drop-off centres. Taken together, these findings support the interpretation that while behavioural change is directly observed under low-friction urban conditions, spatial geography acts as a binding filter on the scale and consistency of comparable outcomes across the wider national system. This baseline provides a useful reference point for interpreting the more pronounced structural and logistical constraints identified in rural municipalities, where the relationship between policy, infrastructure, and realised outcomes is likely to be further conditioned by spatial friction.

Building on this contrast, Paper III shows that infrastructure effectiveness is not uniform across materials or across spatial contexts. The divergence between paper and plastic apparent recovery trajectories suggests that material characteristics and system configuration matter. Paper is heavier, more homogeneous, and often easier to separate cleanly; plastics are lighter, more contamination-prone, and more sensitive to storage, collection frequency, and separation effort. The results suggest that separation varies across plastic-packaging formats: larger and more conspicuous items may be separated relatively consistently, whereas small, lightweight, contaminated, or less salient packages are more likely to remain in the general bin (Thoden Van Velzen et al., 2019). This highlights the clear limits of infrastructure-led reform: persistent material-specific challenges related to polymer heterogeneity, contamination risks, and downstream recycling constraints frequently limit plastic recovery regardless of collection convenience. These downstream constraints also reflect the economics of secondary-material markets. The value and recyclability of recovered plastics vary considerably across polymer types, contamination levels, and market demand, meaning that increased collection does not necessarily translate directly into economically viable material recycling. In a small and remote market such as Iceland, limited domestic processing capacity further increases dependence on external markets for secondary plastics (Mager et al., 2022). The present thesis does not contain transaction-price or market-demand data and therefore cannot determine the extent to which secondary-plastics market conditions contributed to the comparatively weak plastic recovery response. For materials with positive secondary-market value, particularly metals, resale revenues may offset part of the costs associated with collection, handling, and transport. Where such revenues accrue to collection-system operators, they could therefore affect the economics of recycling-centre or specialised collection pathways. However, metals were not included in the empirical analysis in Paper III, and the datasets used in this thesis contain neither material-specific resale revenues nor

information on how such revenues are distributed among municipalities, collection operators, or other actors. The thesis therefore cannot determine whether secondary-metal revenues provide an economic incentive favouring drop-off collection over kerbside collection in Iceland. Moreover, the positive association between drop-off shares and per-capita yields in low-density areas challenges the assumption that kerbside collection is universally superior. The persistence of recyclable materials remaining in the general bin indicates that kerbside infrastructure alone cannot fully eliminate targeted waste from the residual stream. Therefore, further improvements depend increasingly on complementary measures, including targeted communication, contamination control, and the continued use and improvement of drop-off and recycling-centre pathways. In sparse territories, hybrid configurations may reduce transport burden, improve material quality, and better match local logistics (Burns et al., 2021; Keske et al., 2018).

Taken together, these findings reinforce a central insight of this thesis: while institutional reform and infrastructure standardisation can induce measurable behavioural change, the translation of policy into realised outcomes remains systematically conditioned by spatial structure. This interaction between structural constraints, institutional design, and behavioural response forms the basis for the integrated analytical framework developed in the following section.

6.4 An Integrated Analytical Framework: Waste Governance Under Structural Constraints

6.4.1 Conceptual Overview

The central contribution of this thesis lies not in the individual findings of each paper, but in their integration into a unified explanation of how waste management performance emerges under structural constraint. By linking the results across the four papers, a consistent pattern becomes evident: structural conditions (Level I) define the feasible performance space, institutional reforms (Level II) attempt to reshape incentives within that space, and infrastructure (Level III) determines the extent to which behavioural change, and thus policy effectiveness, is realised (Level IV).

The relationship between Papers III and IV is particularly instructive in this regard. Paper III demonstrates that early outcomes under the EPR reform are strongly mediated by operational variables such as collection system design and settlement structure, indicating that institutional harmonisation alone does not guarantee uniform performance. Paper IV builds on this by showing that when infrastructure is standardised and brought closer to households, a measurable and immediate behavioural response follows. Taken together, these findings suggest that the effectiveness of EPR is contingent on the configuration of collection infrastructure, which acts as the primary transmission mechanism between policy and behaviour.

Building upon the initial conceptual framework presented in the introduction (Figure 1), the findings from the three empirical phases allow for the consolidation of this socio-technical system into a more streamlined, explanatory model. By tracing the path from structural constraints (Papers I–II), through institutional reform (Paper III), to realised behavioural outcomes (Paper IV), the research captures the full policy transmission mechanism. Addressing the final research question, the integrated framework developed here, as illustrated in Figure 3, conceptualises circular governance as a four-level, interactive structure. The figure illustrates a four-level system in which structural geographic conditions define the feasible frontier for waste management systems, institutional design translates policy objectives into operational rules, and infrastructure functions as a behavioural interface shaping household responses. These interactions produce observable system outcomes, which in turn feed back into institutional design through policy adjustment and refinement.

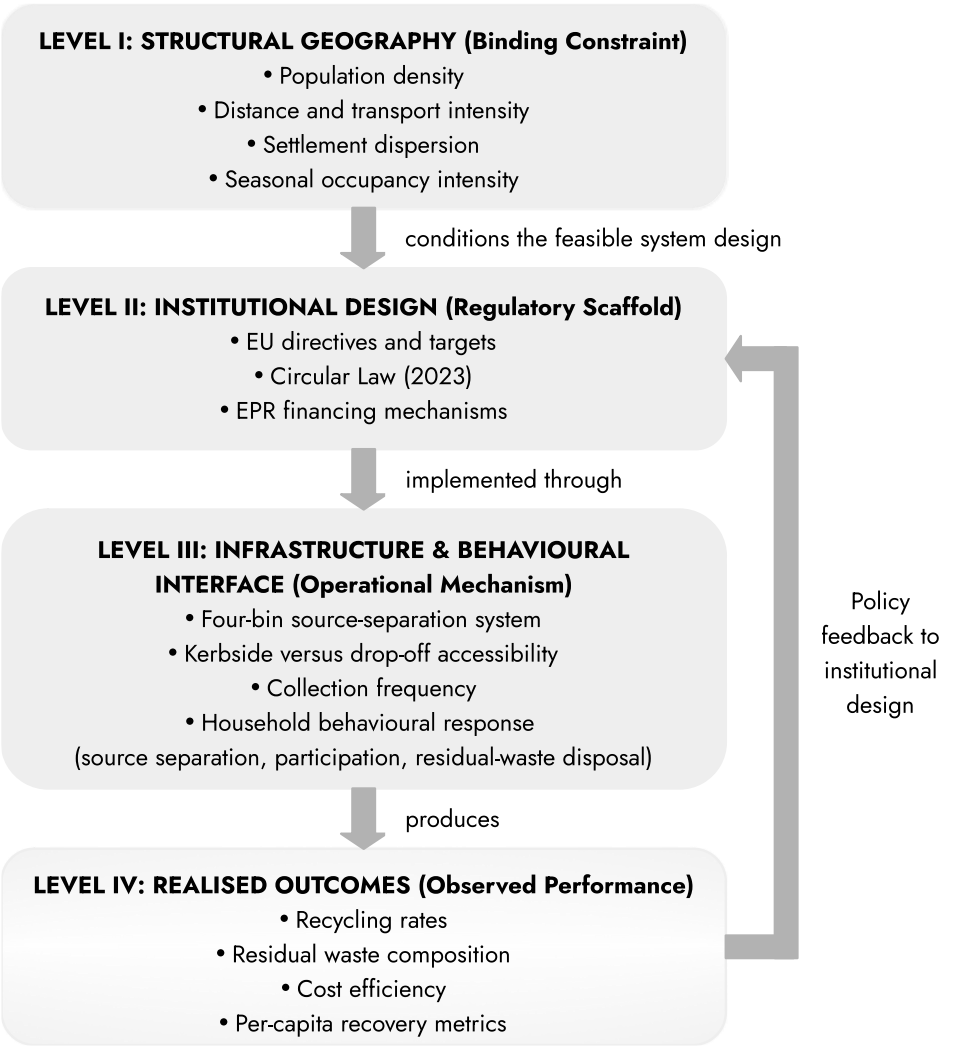


Figure 3. Integrated analytical framework of waste governance under structural constraints. The figure illustrates a four-level model conceptualising the policy filter mechanism. It shows how structural geography (Level I) acts as a binding constraint that filters supranational and national institutional design (Level II). This, in turn, shapes the operational infrastructure interface (Level III), which mediates behavioural responses and produces the realised system outcomes (Level IV). The framework captures how policy interventions are translated into differentiated outcomes across heterogeneous spatial contexts.

At the top, Level I (Structural Geography) acts as a binding constraint that conditions the feasible frontier for policy. This frontier limits how Level II (Institutional Design), the regulatory scaffold, is translated into Level III (Infrastructure Configuration) on the ground. Finally, this operational interface shapes the Level IV (Realised Outcomes) of the entire system.

Each level performs a distinct function, but their interaction determines overall system performance. The central theoretical contribution of this framework is the identification of a filter mechanism: structural geography conditions how institutional reforms translate into infrastructure and, ultimately, behavioural outcomes. While Figure 3 presents a structured hierarchy, it must be interpreted as a quasi-static representation of a highly dynamic socio-technical system. In reality, the municipal waste environment is continuously in motion. The downward translation of policy is not a seamless, continuous flow; rather, it is punctuated by discrete administrative decisions made at the local municipal level at specific points in time to comply with evolving national legislation. Furthermore, the operational reality of Level III frequently necessitates immediate, ad hoc decisions, such as the sudden rerouting or alternative disposal of specific waste streams, when ideal infrastructure pathways are disrupted or temporally constrained. Therefore, the framework captures the structural relationships of the system, even as the operational components remain in constant flux.

6.4.2 The Four-Level Model

Level I: Structural Geography — Binding Constraint

Structural geography represents exogenous conditions that policymakers cannot directly modify in the short or medium term. Population density, distance and transport intensity, settlement dispersion, and seasonal occupancy intensity collectively define the feasible efficiency frontier.

The empirical results in Papers I and II show that these variables materially affect both cost levels and efficiency scores. Geography, therefore, does not merely influence performance; it also bounds the system's performance potential.

Level II: Institutional Design — Regulatory Scaffold

Institutional design includes EU directives, the 2023 Circular Law, and EPR financing and reimbursement rules. This level determines how financial responsibility is allocated and how regulatory targets are operationalised. As Ghisellini et al. (2016) observe, the European circular strategy is characterised by such "bottom-up" environmental and waste management policies, which rely on regulatory frameworks to induce resource efficiency and material recovery at the national level.

The Icelandic reform harmonised financial flows and standardised household obligations. However, as demonstrated in Paper III, institutional harmonisation does not eliminate performance variation. Instead, institutional effects are filtered through spatial and demographic structure.

Level III: Infrastructure Configuration — Operational Interface

At Level III, infrastructure functions as a behavioural interface through which institutional design is translated into household-level responses. The implementation of the four-bin source-separation system, the balance between kerbside and drop-off collection, and overall service accessibility and collection frequency shape the feasibility of household participation. Crucially, because this level relies entirely on human interaction with the physical environment, it acts as a psychosocial filter. It is highly sensitive to qualitative human factors, such as perceived convenience, trust in the recycling system, confusion over contamination, and domestic spatial routines (Struk, 2017; Thøgersen, 2003). While these micro-level frictions are difficult to capture through top-down institutional metrics or aggregate weight data, they strongly influence how sustainably the infrastructure is utilised (Andersson & Stage, 2018; Wilson et al., 2025).

Paper IV demonstrates that infrastructure standardisation can induce measurable structural breaks in disposal behaviour, with the strongest and clearest effect observed in organic waste diversion. However, Paper III shows that infrastructure effectiveness varies across materials and spatial contexts, highlighting the importance of configuration rather than uniform design.

Level IV: Realised Outcomes — System Output

Recycling rates, residual composition, cost efficiency, and per-capita recovery metrics represent cumulative system outputs. These outcomes reflect the "win-win-win" potential of a successful Circular Economy, which Korhonen et al. (2018) define as a system that simultaneously reduces material inputs/outputs (environmental win), lowers raw material and waste management costs (economic win), and fosters a sharing economy with new employment opportunities (social win). However, Level IV outcomes in this framework also account for thermodynamic and governance limits that can prevent these wins from being realised uniformly across space. These outcomes do not reflect institutional design alone; they represent the interaction of all preceding levels. Ultimately, these outputs serve as indicators of what Ghisellini et al. (2016) define as the macro-level objective of the circular economy: achieving a regenerative system that decouples environmental pressure from economic development by increasing the efficiency of resource use.

The identification of denominator distortions linked to seasonal occupancy illustrates that performance metrics themselves are shaped by Level I conditions interacting with Level II reporting standards.

6.4.3 The Filter Mechanism

As visualised in the downward flow of Figure 3, the core theoretical insight of this thesis is that structural geography functions as a filter between institutional intent and realised outcome.

In densely populated continental systems, the friction imposed by Level I conditions is relatively low. Institutional reforms, therefore, translate more directly into infrastructure adaptation and measurable recovery gains.

In sparse, Arctic systems, Level I imposes higher friction. Long distances, seasonal population spikes, and low density attenuate or distort the translation of policy into performance. Financial harmonisation can reduce fiscal asymmetry, and infrastructure standardisation can shift behaviour, but spatial heterogeneity continues to produce differentiated outcomes.

This filter mechanism explains why uniform policy instruments generate non-uniform results across heterogeneous territories.

6.4.4 Transferability and Theoretical Contribution

This thesis advances a socio-technical interpretation of circular economy policy in which institutional design operates at a systemic level by shaping incentives and resource flows, while infrastructure operates at the behavioural interface by determining the accessibility and convenience of participation. The findings suggest that policy effectiveness depends less on uniform regulatory design and more on the alignment between institutional frameworks and context-sensitive infrastructure systems.

Although derived from the Icelandic case, the framework is transferable to other structurally constrained jurisdictions, including island states, archipelagic systems, and remote northern regions (Eckelman et al., 2014; Keske et al., 2018).

The framework contributes to circular economy governance literature in three ways:

1. It integrates efficiency analysis, institutional design, and behavioural infrastructure into a single analytical structure.
2. It identifies spatial asymmetry as a conditioning variable rather than a background characteristic.
3. It conceptualises policy implementation as a filtered translation process rather than a linear transfer from regulation to outcome.

An important cross-cutting finding of this thesis is that performance measurement itself is not neutral, but shaped by underlying structural conditions. In particular, denominator bias introduces a systematic distortion in per-capita indicators in regions

with high seasonal population fluctuations. This creates a disconnect between observed and actual system performance, as municipalities serving large transient populations may appear more efficient or achieve higher recovery rates when measured against resident population figures. This has direct implications for efficiency analysis, as benchmarking based on resident population may systematically misrepresent the performance of municipalities operating under high tourism pressure. In such cases, efficiency scores may reflect denominator artefacts rather than true differences in operational performance.

By foregrounding the interaction between geography and governance, the framework extends existing circular economy scholarship by incorporating the often-overlooked social and ethical dimensions of spatially uneven transitions (Murray et al., 2017). It shifts analytical attention from whether circular policies "work" to the conditions under which they work, and to how their effects are distributed across space. Taken together, the framework provides a system-level explanation of how circular economy policies are translated into differentiated outcomes across heterogeneous territories through a process of filtered policy translation. In doing so, it directly addresses Research Question 4 and constitutes the central theoretical contribution of this thesis.

6.5 Policy Implications

The policy implications of this thesis emerge from the interaction between structural constraints, institutional reform, and observed behavioural outcomes across the four articles. This thesis provides evidence that the effectiveness of circular economy policy in geographically dispersed systems is not determined solely by regulatory ambition or financial incentives, but by how these interact with underlying spatial realities and local service design (Korhonen et al., 2018). The findings yield several policy implications for the design and implementation of waste management systems in Iceland and comparable regions.

6.5.1 Redefining Performance Metrics for Spatial Equity

These findings highlight the need to reconsider how waste management performance is measured and benchmarked in tourism-intensive regions (Arbulú et al., 2024; Rogge & De Jaeger, 2013). The current reliance on resident-based per-capita indicators fails to capture the operational reality of municipalities with high transient populations. Incorporating service-based population metrics, such as guest nights or seasonal occupancy estimates, into performance indicators could provide a more accurate representation of system demand and enable fairer comparison across municipalities (Costa et al., 2025; Mateu-Sbert et al., 2013). Without such adjustments, policy frameworks risk rewarding or penalising municipalities based on measurement artefacts rather than actual performance (Caponi, 2022; Struk & Boďa, 2022). This shift is

essential for ensuring that national circular economy targets are both achievable and equitable across Iceland's diverse geographic landscape.

6.5.2 Enabling Hybrid Collection Designs in Sparse Areas

Collection system design is a primary driver of realised recycling outcomes and must be treated as a central policy variable rather than an operational detail. The findings demonstrate that increasing convenience through universal kerbside collection does not automatically translate into higher material recovery. In low-density and remote municipalities, capacity constraints, such as limited container volume, infrequent collection, and logistical inefficiencies, can offset the behavioural benefits of convenience (Keske et al., 2018). Rather than imposing a rigid universal standard, policy frameworks should empower municipalities to adopt context-sensitive hybrid systems that reflect their logistical realities. By explicitly supporting combinations of kerbside collection and strategically located, well-managed drop-off infrastructure, national frameworks can better accommodate spatial constraints (Xirogiannopoulou et al., 2024). Ensuring that key design parameters, such as container size, collection frequency, and contamination control, are appropriately configured within these hybrid systems is critical for translating policy intent into realised diversion outcomes.

6.5.3 Adjusting Reimbursement to Reflect Spatial Logistics

While current reimbursement mechanisms under the Icelandic Recycling Fund (Úrvinnslusjóður) already incorporate some adjustment for varying service conditions, the empirical evidence in this thesis provides quantitative justification for further calibrating these formulas to more fully offset the rural penalty. Uniform national reimbursement schemes, or those with insufficient geographic weighting, risk penalising municipalities facing inherently higher costs due to distance, dispersion, and climatic conditions (Diggle & Walker, 2022; Leclerc & Badami, 2024). Evidence from Papers I and II demonstrates diminishing returns to expenditure in remote areas, where additional spending is absorbed by transport and logistics rather than improving recycling performance. To address this spatial friction, policy should continue to refine EPR fund allocation formulas by incorporating explicit adjustments for remoteness, transport intensity, and settlement structure. This helps ensure that geographically dispersed municipalities are not systematically disadvantaged by factors beyond their control, while preserving incentives for efficiency (Bel & Fageda, 2010).

6.5.4 Harnessing Intermunicipal Cooperation

Iceland already possesses established models of intermunicipal waste cooperation (such as SORPA in the Capital Region and various rural equivalents). The Data Envelopment Analysis (DEA) findings in this thesis quantitatively validate these arrangements, demonstrating that such cooperation is not merely an administrative convenience but a structural necessity for mitigating the scale diseconomies observed

in remote areas. While the 2023 reform focused on financial harmonisation via EPR, both international evidence and the structural constraints identified in this research suggest that expanding intermunicipal cooperation remains a critical tool for improving efficiency and service quality in small municipalities (Bel & Mur, 2009). Future policy should therefore focus on deepening and formalising these networks, encouraging rural municipalities to cooperate in service delivery to offset the spatial penalties identified in this thesis (Bel & Fageda, 2010).

6.5.5 Aligning Policy With Physical Infrastructure

The results highlight the importance of aligning policy instruments with the physical infrastructure through which behavioural change occurs. The introduction of harmonised EPR financing provides a necessary regulatory and financial scaffold, but behavioural outcomes, such as greater household source separation and reduced residual waste, are realised only when supported by accessible and appropriately designed infrastructure (Andersson & Stage, 2018; Struk, 2017). This underscores the need for an "infrastructure-first" approach to policy implementation, where investments in collection systems and service accessibility are prioritised alongside regulatory reform.

Building on this, the findings suggest that equitable access to source-separation infrastructure is a key determinant of public participation. However, in spatially heterogeneous environments, equity does not necessarily imply identical service delivery. Context-adapted systems that balance kerbside and drop-off solutions can mitigate local spatial friction, reduce disparities in participation, and support more stable household separation behaviour. Infrastructure design is therefore not merely a logistical consideration but also a determinant of system performance and equity within circular economy systems.

6.5.6 The Limits of Policy Transfer

The findings suggest that policy transfer from high-density continental systems to small, geographically dispersed contexts requires careful adaptation. Standardised policy models, including EPR schemes and recycling targets, often assume conditions of scale, density, and logistical efficiency that do not hold in Arctic or rural regions (Burns et al., 2021; Eisted & Christensen, 2011). The Icelandic case demonstrates that achieving circular economy objectives under such conditions requires flexible policy design, differentiated implementation strategies, and performance metrics that reflect local realities.

Taken together, these implications suggest the limits of standard policy transfer. In this sense, effective circular economy governance in spatially constrained systems requires not only harmonised policy instruments but differentiated implementation strategies that explicitly account for geographic, infrastructural, and demographic heterogeneity.

6.6 Limitations and Future Research Directions

While this thesis provides a system-level evaluation of waste management transitions in Iceland, several limitations must be acknowledged. These limitations define the scope of the findings and indicate directions for future research on circular governance in spatially constrained environments.

6.6.1 Data Granularity and Behavioural Attribution

A primary limitation of this research relates to data granularity and the challenge of behavioural attribution. While the thesis provides evidence consistent with denominator bias and proposes the use of service-population metrics in Papers I and III, its reliance on aggregate municipal-level data limits the ability to distinguish household separation behaviour among different population groups. Even when refined proxies for seasonal occupancy are used, such as the cottage ratio employed in Paper III, or alternative indicators such as guest nights, it is not possible to determine definitively the relative contributions of permanent residents and transient populations, including tourists and seasonal workers.

Consequently, although the research clarifies how measurement artefacts may influence observed performance, it cannot isolate the precise quantity of waste generated by specific demographic groups. Future research using seasonal waste-composition analysis, based on the manual sorting of residual-waste samples collected at different times of the year, would provide a more direct link between system performance and user behaviour.

A further structural data constraint concerns the separately collected paper and plastic packaging data used in Papers III and IV. Because these streams were not manually characterised, the available quantities are based on gross collected weights and are not adjusted for moisture, contamination, or other non-target materials. In Paper IV, the resulting apparent capture rates should therefore be interpreted as operational indicators of collection and diversion performance rather than purity-adjusted material recovery rates. In addition, an unquantified share of the material collected through public drop-off containers and recycling centres may originate from small commercial users rather than households. This systemic limitation in municipal waste reporting explains why the central behavioural findings of Paper IV rely primarily on the manual characterisation of general-bin contents, which is substantially less sensitive to contamination and moisture distortions in separately collected streams.

A further temporal limitation concerns the short chronological post-reform period in Paper IV. The analysis currently includes only three post-reform years, of which 2023 was a partial implementation year. Although the spatial panel provides 15 post-reform observations across five analytical areas, the limited chronological follow-up means that the results provide stronger evidence regarding immediate level changes than long-

term trends or behavioural persistence. Continued monitoring is therefore needed to determine whether the initial reductions are sustained as the four-bin source-separation system and associated household practices become embedded in everyday routines.

6.6.2 Spatial Transferability and the Urban–Rural Divide

The behavioural evidence presented in Paper IV is based on longitudinal waste-characterisation data from the Capital Region, which functions as an urban baseline for evaluating the 2023 reform. This design reflects both a methodological choice and a data constraint. Establishing system performance under conditions in which spatial friction is relatively limited provides a useful reference point for interpreting variation across municipalities. The results show that implementation of the four-bin source-separation system was associated with a substantial structural break in residual-waste composition in a dense and comparatively well-resourced context.

At the same time, restricting the analysis to the Capital Region limits the direct transferability of the findings to Iceland's smaller and more remote municipalities, where structural and infrastructural constraints are more pronounced. In these contexts, the relationship between policy, infrastructure, and household behaviour may be further conditioned by transport distance, collection frequency, housing configuration, service capacity, and access to complementary drop-off facilities.

This limitation is partly driven by data availability, as the continuous, high-quality waste-characterisation data based on physical sampling, manual sorting, and weighing that are required for a robust Interrupted Time Series design are currently available only within the SORPA system. Extending the ITS approach to rural municipalities as comparable data systems mature would provide a more comprehensive assessment of how spatial dispersion influences the speed and magnitude of reform-associated changes in household disposal behaviour.

6.6.3 The "Day-Tripper" Gap and Dynamic Service Loads

Although this thesis advocates a shift toward service-population metrics, available proxies (such as cottage counts or registered guest nights) do not capture non-overnight transient populations, such as day-trippers and cruise passengers. In high-intensity tourism regions, these groups may contribute significantly to waste generation without being reflected in conventional denominators.

This unmeasured transient load may also confound the interpretation of infrastructure performance. For example, the higher per-capita yields observed in rural municipalities relying heavily on drop-off centres (Paper III) may partly reflect disposal patterns of visitors. Because these users lack access to residential kerbside bins, they are more likely to use public drop-off facilities, rather than the observed differences being solely attributable to system performance among permanent residents.

This limitation highlights the need for more dynamic representations of service demand. Future research could incorporate alternative data sources, such as mobile network data, traffic flows, or location-based indicators, to construct more accurate estimates of real-time service loads. Such developments would improve both performance measurement and infrastructure planning in regions characterised by high demographic volatility.

6.6.4 From Recovery to Prevention: The Hierarchy Gap

This thesis primarily focuses on material recovery (recycling) and the diversion of organic waste, reflecting the immediate priorities of the 2023 Circular Law. However, higher levels of the waste hierarchy, particularly waste prevention and reuse, remain underexplored in the Icelandic context.

As collection infrastructure matures, future research should expand its focus toward the role of institutional incentives (Level II) in reducing waste generation and the potential for infrastructure systems (Level III) to support reuse, repair, and second-hand markets. This shift would enable a more comprehensive evaluation of circular economy transitions beyond recovery-based metrics.

6.6.5 Future Research Agenda

Building on these findings, future research can advance the socio-technical understanding of circular transitions in several key ways.

First, the development of integrated service-load models that combine tourism indicators with seasonal occupancy would improve forecasting and infrastructure planning in regions with significant demographic fluctuations (Arbulú et al., 2024; Caponi, 2022). Second, as the 2023 reform progresses beyond its initial implementation phase, further research should examine behavioural persistence, identifying the mechanisms that sustain household participation in source separation once the initial adjustment period has passed. Third, improved standardisation of municipal accounting and reporting systems would reduce the structural data limitations identified in this thesis and enable more robust and comparable performance assessments. Fourth, complementing this system-level analysis with qualitative approaches, such as household interviews or ethnographic observation, would provide deeper insight into the behavioural processes underlying observed source-separation patterns. Finally, a further extension would be to examine livestock waste, agricultural residues, animal mortalities, and rendering streams as a separate component of rural circular-economy governance, particularly in relation to nutrient recovery and the integration of agricultural and municipal material flows.

7 Conclusions

This thesis set out to examine the implementation of circular economy transitions under conditions of extreme spatial asymmetry. The empirical findings provide strong evidence that while Iceland's 2023 Extended Producer Responsibility (EPR) reform established a vital financial and regulatory scaffold, realised performance is heavily mediated by local geography and infrastructure. As conceptualised in the integrated four-level framework, circular economy outcomes do not follow a linear path from policy to practice. Instead, they emerge through a hierarchical filtering mechanism in which structural geography (Level I) conditions how institutional design (Level II) is translated into infrastructure configuration (Level III) and, ultimately, household behaviour. Consequently, in geographically constrained systems, policy effectiveness depends not only on regulatory ambition but on the alignment between these system levels.

Main Conclusions:

1. Structural geography defines the feasible efficiency frontier: Standard efficiency metrics fail to capture the operational realities of Arctic and low-density systems. Structural conditions such as spatial dispersion and transport intensity act as binding constraints that shape cost efficiency, indicating that high service costs in remote areas primarily reflect geographic conditions rather than managerial inefficiency.

2. Demographic volatility systematically biases performance metrics: In tourism-intensive economies, per-capita indicators based on resident populations are affected by denominator bias. Seasonal population fluctuations can inflate or depress observed outputs, leading to misleading comparisons. This highlights the need to adapt institutional design, particularly EPR reimbursement models, to service-population metrics.

3. Infrastructure functions as the primary interface for behavioural change: Evidence from Iceland's urban baseline shows that the rollout of the harmonised four-bin source-separation system was associated with a clear structural break in waste composition, particularly through increased organic-waste diversion. This indicates that physical accessibility is a critical mechanism through which policy is translated into household behaviour. Synthesis with the structural constraints identified in earlier phases suggests that the scale of comparable effects in remote municipalities is likely mediated by the spatial and infrastructural constraints of dispersed systems.

4. Behavioural gains may not be self-sustaining: Early signs of performance stabilisation suggest a tendency for initial participation gains to diminish over time, highlighting the need for sustained engagement and system refinement.

5. Institutional harmonisation alone does not ensure uniform outcomes: While the EPR reform standardised financial responsibility and regulatory obligations, performance variation persisted across municipalities. This reflects the filtering effect of structural geography, which shapes how policy is operationalised in practice. Effective governance, therefore, requires aligning institutional design with locally feasible infrastructure configurations.

Ultimately, effective waste governance in geographically dispersed economies requires a differentiated approach. While financial responsibility and environmental targets can be centralised and harmonised through instruments such as EPR, operational systems must remain adaptive and responsive to service-population dynamics, material-specific constraints, and the physical realities of dispersed territories. Only by explicitly designing for these structural filtering mechanisms can circular economy policies achieve more consistent and equitable outcomes.

7.1 Implications, Policy Relevance and Transferability

The conclusions above summarise what this thesis has shown about circular economy governance under structural constraint. This section considers what these findings mean in practice for Icelandic waste policy, how they may inform future policy evaluation, and to what extent the underlying mechanisms and analytical lessons apply beyond the Icelandic case. The aim is not to repeat the detailed policy implications presented in Section 6.5, but to draw together the principal practical lessons of the four studies and clarify their broader relevance.

7.1.1 Implications for Icelandic Waste Governance

As implementation of Iceland's 2023 waste-management reform moves towards consolidation, the findings of this thesis point to four areas that are particularly relevant for future evaluation and refinement: the measurement of municipal performance, the design of producer-funded reimbursement, the durability of household source-separation behaviour, and the longer-term balance between domestic and cross-border treatment capacity.

The first concerns the measurement of municipal performance. Waste-management indicators expressed on a per-capita basis rely on registered resident populations as their denominator. Paper III shows how this can distort comparisons in municipalities with substantial seasonal housing and visitor populations, because the waste system serves a larger and more variable population than the official resident count suggests (Arbulú et al., 2024; Caponi, 2022). The findings therefore support the use of

supplementary service-population indicators, such as guest nights, seasonal occupancy estimates, or holiday-home measures, when interpreting municipal performance (Costa et al., 2025; Mateu-Sbert et al., 2013). Such indicators would not replace conventional population statistics, but they would provide a more equitable basis for comparing municipalities operating under different service loads.

The second concerns the allocation of producer-funded reimbursement. Paper I documents a near fourfold difference in per-capita waste-management expenditure between the smallest and largest municipalities, approximately €379 against €106 (Óskarsson et al., 2022), while Paper II shows that measured performance is strongly conditioned by population size, geographic scale, and related structural characteristics. Together, these findings provide an empirical basis for assessing whether reimbursement arrangements under the Icelandic Extended Producer Responsibility framework adequately reflect remoteness, transport intensity, and settlement dispersion (Bel & Fageda, 2010; Leclerc & Badami, 2024). A nationally harmonised financing framework can reduce fiscal disparities, but it does not remove the underlying logistical differences between municipalities.

The third concerns the durability of household behavioural change. Paper IV identifies a substantial post-reform decline in material remaining in the general bin in the Capital Region, including an approximately 37% reduction in total general-bin waste and a 54% reduction in biodegradable material in the residual stream. These findings indicate that accessible household-level source-separation infrastructure can produce a marked change in disposal behaviour. The slight stabilisation observed in 2025 nevertheless underlines the importance of continued monitoring. Maintaining performance is therefore likely to depend not only on infrastructure, but also on clear information, contamination control, household feedback, and complementary collection channels (Thøgersen, 2003; Wilson et al., 2025).

The fourth concerns the balance between domestic and cross-border treatment, and it bears directly on how Iceland's landfill dependence should now be characterised. Paper I documented the scale of that dependence before the reform, with more than 60% of municipal solid waste landfilled or incinerated without energy recovery, against an EU-27 landfill rate of approximately 24% at the time (Óskarsson et al., 2022), and this remains an appropriate pre-reform baseline. Since then, domestic landfilling has declined markedly. In the Capital Region, an important part of this reduction reflects the decision to discontinue landfilling of mixed residual household waste and instead export it to Sweden for incineration with energy recovery, and SORPA (2026) reports that more than 45,000 tonnes were redirected through this route in 2025. Export-based treatment is not confined to the Capital Region. Two private waste-management companies with extensive operations in Iceland, Íslenska Gámafélagið and Terra, also export substantial waste streams for treatment abroad. Íslenska Gámafélagið reports exporting approximately 60,000 tonnes to Europe in 2025, including 31,700 tonnes of

general waste for energy recovery, while Terra reports that the export for energy recovery of material previously sent to landfill has become an increasingly important part of its operations (Íslenska Gámafélagið, 2026; Terra, 2026). Available company data do not, however, provide a consistent municipality-level breakdown of these exports or, in all cases, their final destinations.

National figures indicate that the landfill rate for municipal waste had fallen to approximately 10% by 2024, bringing Iceland to the 10% threshold set by the Landfill Directive for 2035 well ahead of schedule (*Mælaborð | Úrgangur.is | Umhverfis- og orkustofnun*, 2025). On the landfill metric, therefore, the characterisation of Iceland as among the most landfill-dependent countries in Europe no longer holds. The nature of the system's dependence has, however, partly shifted rather than disappeared. Performance against European waste-management targets is now more mixed than the pre-reform picture suggested. By 2024, Iceland had approached the targets for household-waste recycling and construction and demolition recovery, and had exceeded the targets for end-of-life vehicle recovery, while substantial gaps remained in some other streams (*Mælaborð | Úrgangur.is | Umhverfis- og orkustofnun*, 2025). At the same time, a substantial share of the reduction in landfilling reflects the redirection of residual waste to treatment abroad rather than increased domestic material recovery.

This development represents a significant movement away from landfilling, but it should not be interpreted as an equivalent increase in material circularity. Energy recovery occupies a higher position in the waste hierarchy than disposal, but it does not return materials to productive use in the same way as recycling. The evidence from Paper IV therefore identifies a distinct and complementary development: a substantial reduction in biodegradable material remaining in household residual waste, consistent with a change in household source-separation behaviour rather than solely a change in final treatment destination. As noted in Section 6.3, however, diversion from the residual bin is not equivalent to verified material recovery, because the composition and purity of the separately collected organic fraction were not independently characterised. The national decline in landfilling should accordingly be interpreted in light of both increased separate collection and a broader shift towards cross-border treatment, although the relative contribution of these mechanisms cannot be quantified consistently across municipalities.

The growing role of cross-border treatment raises a further strategic question concerning the balance between export and domestic processing capacity. The present Icelandic system already reflects a mixture of these approaches: substantial quantities of residual waste and recyclable materials are exported for treatment abroad, while some streams, most notably biodegradable kitchen waste, can be processed domestically. At the same time, Icelandic authorities and municipalities have for several years examined the feasibility of developing domestic waste-to-energy incineration capacity as part of the longer-term transition away from landfilling. Paper I discusses assessments of both a

larger centralised facility near the Capital Region and smaller regional alternatives, highlighting the trade-off between economies of scale and transport distances (Óskarsson et al., 2022). Paper II similarly notes that the absence of domestic high-capacity incineration infrastructure has coincided with increasing reliance on waste exports (Óskarsson et al., 2025). This illustrates a structural trade-off for a small island economy. Cross-border treatment can provide access to specialised facilities and economies of scale that may not be economically viable domestically, but it also creates dependence on external treatment markets and transport. Developing additional domestic capacity could reduce that dependence, but would require sufficient material volumes, substantial capital investment, and a viable use for the recovered energy. This thesis does not evaluate the relative economic or environmental merits of these alternatives, but its findings on scale, transport costs, and geographic constraints indicate that the trade-off should be assessed explicitly in decisions on Iceland's longer-term treatment infrastructure.

This trade-off also illustrates the four-level framework developed in this thesis and the multi-level governance structure within which Icelandic waste policy is implemented. Structural geography constrains the scale and location of viable treatment infrastructure, while national regulation, producer-responsibility financing, municipal service responsibilities, and private waste-management operators interact in shaping how those constraints are managed. The resulting infrastructure choices in turn shape the downstream recovery pathways available. The fact that a harmonised national reform has been accompanied by increased reliance on treatment abroad can therefore be interpreted through the filtering mechanism described by the framework: common circular-economy objectives are translated into different operational outcomes under Iceland's spatial and economic conditions.

7.1.2 Policy Relevance and Future Engagement

The 2023 reform was enacted before the main empirical results of this thesis became available. The research therefore evaluates the implementation and early outcomes of the reform rather than having shaped its design, and the findings have not to date influenced legislation or documented changes in national waste-management policy. Dissemination during the doctoral period has mainly concerned the earlier stages of the research, particularly the findings of Papers I and II on municipal cost differences, efficiency, and structural constraints. Papers III and IV were published in 2026 and have therefore had limited opportunity to enter public or policy debate. Their dissemination has so far been largely confined to academic settings, with broader communication beginning as the doctoral project reaches completion.

The relevance of the thesis lies accordingly in the decisions still ahead. Four areas are particularly relevant. Future review of Act No. 103/2021 can assess whether harmonised obligations have produced equitable outcomes across municipalities,

which is precisely the question Paper III addresses. Reimbursement arrangements under the Recycling Fund can be evaluated against the cost and efficiency evidence in Papers I and II. National performance reporting can incorporate service-population adjustments, for which Paper III provides both the rationale and a workable proxy. Municipal decisions on collection-system design can draw on the finding that drop-off and kerbside collection perform differently across spatial contexts and material fractions.

More broadly, the four-level framework may support ex-post regulatory impact assessment by providing a structured way to examine how regulatory objectives are translated through structural conditions, institutional arrangements, and operational infrastructure into observed outcomes. This is particularly relevant in the Icelandic context, where a nationally harmonised reform operates across municipalities facing markedly different spatial and service conditions.

Continued empirical evaluation should accompany this. As additional post-reform observations accumulate, extending the Interrupted Time Series analysis will provide stronger evidence on whether the behavioural changes identified in Paper IV persist. Comparable waste-characterisation data from municipalities outside the Capital Region would allow the findings to be tested under more pronounced conditions of remoteness and settlement dispersion, and would address the principal spatial limitation of the present evidence base.

7.1.3 Transferability Beyond Iceland

The findings differ in how readily they transfer. Transferability should be understood primarily in terms of mechanisms, analytical approaches, and policy-design principles rather than the direct transfer of Icelandic effect sizes or institutional arrangements.

The denominator-bias finding is the most broadly transferable. It applies wherever the population served by municipal waste systems diverges substantially from the registered population, including tourism-intensive islands, coastal regions, mountain resorts, and areas with large numbers of second homes (Arbulú et al., 2024; Costa et al., 2025; Mateu-Sbert et al., 2013). In such settings, high per-capita recovery or waste-generation figures may partly reflect an inappropriate denominator rather than unusually strong or weak household behaviour.

The spatial-constraint findings of Papers I and II transfer most directly to sparsely populated and peripheral jurisdictions, including northern regions of Norway, Sweden and Finland, Greenland, the Faroe Islands, and remote communities in northern Canada and Alaska, where low density, long transport distances and limited economies of scale create comparable conditions (Burns et al., 2021; Eisted & Christensen, 2011; Keske et al., 2018). The transferable lesson here is methodological: benchmarking

should account explicitly for structural geography before measured performance differences are interpreted as managerial inefficiency.

The EPR findings are relevant to any jurisdiction applying nationally harmonised producer-responsibility systems across heterogeneous territories. Paper III shows that a common financial and regulatory framework does not produce uniform outcomes when operational conditions differ substantially between municipalities. Iceland illustrates this clearly because financial responsibility is centralised while municipalities retain responsibility for collection and service organisation. Uniform producer financing can therefore reduce fiscal asymmetry without eliminating operational asymmetry (Campbell-Johnston et al., 2021; Joltreau, 2022).

The behavioural findings of Paper IV transfer most readily to urban or relatively well-resourced systems introducing separate collection of biodegradable waste, as required across the European Economic Area under the amended Waste Framework Directive (European Commission, 2018). Direct transfer should remain cautious, since the Capital Region differs substantially from Iceland's most remote municipalities.

Transferability is more limited in contexts where low population density, settlement dispersion, and long transport distances are not the dominant constraints, including dense urban systems in Europe and Asia. In such settings, other factors, such as land scarcity, treatment capacity, collection intensity, housing form, or institutional structure, may play a greater role. The denominator mechanism, by contrast, remains relevant in island and archipelagic systems with high visitor loads anywhere. Several features of the Icelandic case also limit institutional transfer, including its small national scale, EEA membership, concentrated population distribution, state-administered Recycling Fund, and reliance on cross-border treatment for parts of the recovered material stream. The four-level framework should accordingly be understood as an analytical structure for examining policy translation under spatial constraint, not as a universal institutional model.

7.1.4 Lessons for Island States and Peripheral Regions

Five lessons emerge for northern island states and other peripheral regions seeking to implement circular economy reform under comparable conditions.

First, performance should be assessed against the population actually served wherever possible, rather than relying exclusively on registered residents.

Second, kerbside and drop-off collection are better understood as complementary options whose suitability depends on density, distance, material characteristics, and service demand, rather than as a hierarchy in which kerbside collection is uniformly superior (Xirogiannopoulou et al., 2024).

Third, EPR can redistribute financial responsibility for recovery but cannot remove the physical costs imposed by geography, so reimbursement systems may need to recognise structural differences in transport intensity and settlement dispersion.

Fourth, infrastructure is a necessary but not always sufficient condition for sustained performance. The stabilisation observed in 2025 reinforces the need to examine complementary measures for maintaining participation over time. Economic instruments such as pay-as-you-throw schemes represent one possible avenue for future research, although their suitability in dispersed areas and locations with large transient populations would require careful evaluation (Dijkgraaf & Gradus, 2015; Fullerton & Kinnaman, 1996).

Fifth, small and remote systems face a structural constraint on downstream markets. Limited volumes restrict the scope for domestic reprocessing, leaving a genuine trade-off between exporting recovered material and developing local treatment capacity. Among the principal household fractions examined in this thesis, biodegradable kitchen waste differs in that a substantial local treatment pathway exists, whereas several recyclable material streams remain dependent on export markets.

Reform should be accompanied by investment in consistent and comparable data throughout. Reliable information on waste quantities, composition, collection channels, service populations, costs, and final treatment is a precondition for meaningful evaluation, and the data constraints documented in Section 4.3 are themselves partly a product of the same territorial fragmentation that shapes waste governance.

Taken together, these lessons reinforce the central conclusion of this thesis: structural constraints are not peripheral complications in the transition to a circular economy, but important determinants of how common policy objectives are translated into practice. Harmonised regulatory frameworks and producer-responsibility arrangements can establish common objectives and financial responsibilities, but they do not remove territorial heterogeneity. Their effectiveness depends on how institutional arrangements, infrastructure, financing mechanisms, performance measures, and service configurations interact with local spatial conditions. For Iceland and comparable peripheral systems, effective circular economy governance therefore requires not uniformity of implementation, but sufficient flexibility to pursue common objectives under different operating conditions.

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Country report

Waste management in Iceland: Challenges and costs related to achieving the EU municipal solid waste targets

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ABSTRACT

Waste management in Iceland has developed considerably in recent years. Before 1990, most of the waste was either burnt in open pits or landfilled. In the past, information about waste management in Iceland used to be almost exclusively published in reports and was primarily based on rough estimates. Currently, incinerators and landfilling sites are highly regulated and follow EU legislation. Additionally, reporting has gradually improved and is approaching EU standards, although improvement is still needed. In an international context, Iceland is far behind the other Nordic countries as well as the EU-27 countries in reducing landfill rates and enhancing energy recovery and recycling rates. According to the EU landfill directive, the total amount of municipal solid waste (MSW) landfilled must be below 10% by 2035; however, it is currently over 60%. Other targets are similarly far off, and it is unlikely that Iceland will meet those in time without immediate and significant changes in waste management. This article aims to evaluate MSW management in Iceland at the national and regional levels, its compliance with the EU's targets for waste management and the associated costs inflicted on municipalities. Hence, annual accounts data were used when comparing regions and municipalities. It was found that there are significant differences in per capita waste management expenditure between municipalities with less than 1,000 inhabitants (€379) and ones with more than 10,000 inhabitants (€106). Without changes in proposed future waste management strategies, this gap will inevitably increase in the upcoming years.

1. Introduction

Iceland is an island in the North Atlantic, just south of the Arctic Circle, with a subpolar oceanic climate. Like many other remote areas in the polar and subpolar regions, Iceland has small, diffused populations. Indeed, Iceland is one of the most sparsely populated countries in the world, with a population density of just under 3.5 persons per square kilometre. Nearly 64% of the inhabitants live in the capital region which covers 1% of the total area of the country. Only around 20% of the population live more than 50 km away from the capital, mostly in smaller towns/villages on or near the coastline or in rural areas, often with long distances between settlements. Due to the difficult terrain with mountains, glaciers and lava fields, few people reside in the island's interior. The road transport system reflects this as well, with most roads hugging the coastline and many being woefully inadequate.

The harsh climate, unbalanced population and often long transportation distances to urban areas, as well as lack of resources, (Eriksen et al., 2020, Solvang et al., 2013), can all result in waste being stored for long periods with an increasing need for storage facilities and associated costs (Keske et al., 2018). Because of these issues, remote areas in the north often have less developed infrastructures than more populous areas within the same country, as well as more lax regulations, or have to rely on exemptions (Eisted & Christensen, 2011, Granberg et al., 2017).

Little is known about waste management in Iceland before 1970, with waste in general being dumped into the sea, burned or landfilled (Meyles, 2006). From 1970 to 1990, waste was increasingly landfilled and burned in controlled open pits, in addition to three incinerators being built (Meyles, 2003). While data on the amount and composition of waste from this period is unavailable, changes were made towards more sustainable waste management. The first pollution control regulation in Iceland was issued in 1990, and the Ministry of Environment was established in the same year (now Ministry for the Environment, Energy and Climate). Following this, a waste management plan was put

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into action, focusing on organised data collection and the requirement of operating licences for all business operations relating to waste management. In 2003, Act 55/2003 on waste management was enacted with article 5 stating that the Minister for the Environment, Energy and Climate shall issue a waste management policy, based on the proposal of the Environment Agency of Iceland. Article 6 of the same law states that municipalities, one or more, shall jointly draw up regional waste management plans based on national policy. In 2020, 58 out of 69 municipalities were members of regional plans that can be accessed from the Icelandic Association of Local Authorities' website (https://www.samband.is). The remaining 11 municipalities did not submit plans. A new waste management policy was not released until June 2021 (Ministry for the Environment and Natural Resources, 2021), delaying regional plan submissions that were written from 2005 to 2015, which by law must be reviewed every six years.

Currently, the most common methods for municipal solid waste (MSW) disposal in Iceland are landfilling and other conventional methods. In 2000, the landfilling rate was 75% but has since then been slowly declining. In 2019, the total amount of MSW in Iceland was about 237,000 tonnes, with 61% or 144,000 tonnes landfilled or incinerated, of which ca. 3,100 tonnes were exported abroad for incineration with energy recovery, and the remaining 39% were either recycled or reused (The Environment Agency of Iceland, 2021b). New waste management policies aim to make major changes to the current state of affairs, increase sustainability and move towards a circular economy (Ministry for the Environment and Natural Resources, 2021).

In this article, we will evaluate MSW management in Iceland and its compliance with the EU's targets in waste management. Comparisons with the other Nordic countries will also be provided. Such analysis is of special relevance, as the Nordic countries share a similar climate, remoteness of rural communities, the importance of social democracy, and enjoy close relationships, such as through the Nordic council. Within Iceland, expenditure on waste management at municipal level will be examined with reference to region and population size. Finally, we will discuss why Iceland has lagged behind other comparative countries, such as the Nordics countries.

Several publications have touched on the subject of waste management in Iceland (e.g. Davíðsdóttir & Agnarsson, 2010, Fischer, 2013, OECD, 2014, Papineschi et al., 2019, Cook et al., 2017, Ministry for the Environment and Natural Resources, 2018, Finger et al., 2021). In addition, several studies have been published in recent years on waste disposal technologies and waste to energy technologies for organic waste in Iceland (Safavi and Unnthorsson, 2017, Safarian and Unnthorsson, 2018, Safarian et al., 2020a, Safarian et al., 2020b). However, to date, there have been no articles published in English in academic journals on MSW management in Iceland and municipal expenditure on waste management.

2. Background

Iceland is a member of the European Economic Area (EEA) which is most relevant when it comes to waste management, as the membership binds Iceland to implement EU environmental directives. In 1975, the EU adopted the Waste Framework Directive (75/442/EEC) (Farmer, 2012) which formed the basis of the regulatory structure of waste. This framework included the first set of laws to protect the environment in the EU and introduced the 'polluters pay' principle, the notion that the objective of waste disposal is the protection of human health, and stressed the need for community action, among other things. Most recently, the EU has worked towards turning the European economy towards a circular economy, aiming to treat waste as a resource and ensure less waste (European Commission, 2020). This fits with the strategic direction of the EU environmental policy and sets a vision where nothing is wasted, and natural resources are managed sustainably by 2050 (Lee et al., 2017). With the implementation of the package, there were key changes to pre-existing framework relating to waste management, namely the Waste Framework Directive, Landfill Directive, and Packaging and Packaging Waste Directive (Papineschi et al., 2019).

Amendments to the Waste Framework Directive (EU 2018/851) (European Commission, 2018b) require member states to improve waste management systems via sustainable material management, improve resource use efficiency, and ensure that waste is valued as a resource. The specific EU targets set for recycling and landfilling MSW are listed in Table 1, which for comparison also shows the current status in Iceland.

2.1. Waste management in Northern regions

Despite most northern communities' remoteness, over four million people live above the Arctic Circle (Bogoyavlenskiy & Siggner, 2004). Due to climate, long distances and low population densities, waste management can be highly challenging. Even in large settlements, such as Irkutsk in eastern Siberia, with close to 600,000 inhabitants, the costs associated with the transport of waste have made recycling unattainable and resulted in 97% of waste being landfilled (Starostina et al., 2014, Starostina et al., 2018). In this case, recyclable materials often have to be transported over 3,000 km at a high cost, thereby producing large quantities of pollution, making landfilling much more cost-effective. As a result, constructing landfills that minimise environmental impact by reducing leachate is a priority (Starostina et al., 2014, Lebreton & Andrady, 2019). A similar situation, albeit less extreme, can be seen in Lapland, where the number of landfills has gone from 100 to three, meaning that waste needs to be transported hundreds of kilometres for landfilling, and even longer for recycling (Tomperi et al., 2017). A similar trend can be observed with the closing of local incinerators in Finland. The result of such closing of landfills and local incinerators has, in some cases, led to increased illegal disposal rates (Keske et al., 2018). To reduce the risk of such illegal disposals, in some areas, the cost of waste management is covered exclusively by the municipality (Keske et al., 2018), or covered by a combination of the fee paid for collection by individuals and other costs borne by municipalities (Eisted & Christensen, 2011). In more populous areas, municipalities often outsource waste collections, while more rural municipalities are more likely to manage their own waste collection (Eisted & Christensen, 2011).

Northern regions, including parts of the Nordic countries, are particularly sensitive to environmental and climate change (Moon et al., 2019). To counter any potential impact, Nordic countries aim to increase sustainability and implement a circular economy (Nordic Council of Ministers, 2020). One of the commonalities between the Nordic countries is that municipalities are in charge of waste management, and while the legal framework limits competition in waste management to some extent, deregulation in some parts of the waste management sector

Table 1
European targets on recycling and landfill and the state of affairs in Iceland.

	European targets on recycling and landfill			Iceland
Year	2025	2030	2035	2019
Maximum target				
Landfill rate			10%	56
Minimum targets				
Waste diversion through reuse and recycling	55%	60%	65%	27%
Packaging waste	65%	70%		47%
plastic	50%	55%		25%
wood	25%	30%		16%
ferrous metals	70%	80%		43%
aluminium	50%	60%		86%
glass	70%	75%		0%
paper and cardboard	75%	85%		89%

(European Commission, 2018a, European Commission, 2018b, European Commission, 2018c), Icelandic data are based on Ministry for the Environment and Natural Resources, 2021.

has opened up avenues for competition (Nordic Competition Authorities, 2016).

In the past, most Nordic countries would try to manage waste through various means such as taxation, Pay As You Throw systems – based on weight, volume or waste type – and home collections of recyclables rather than Bring Banks (Heller & Vatn, 2017, Thøgersen, 2003). The negative side of using weight- or volume-based fees is that the risk of unwanted and illegal disposal increases (Heller & Vatn, 2017, Dijkgraaf & Gradus, 2017). In all the Nordic countries, municipalities have exclusive rights to household waste management, meaning that inhabitants cannot choose a service provider that would allow for competition in the market (Nordic Competition Authorities, 2016). Businesses and industries in the Nordic countries are not limited in the same way in terms of waste management service providers and mostly use private companies to collect and dispose of waste, based on municipal and governmental regulations. In practice, many municipalities contract private companies to handle the waste collection and running of facilities such as landfills, incinerators, and recycling centres. In general, privatisation of waste management is increasing in all Nordic countries, although carefully regulated and managed by municipalities (Papineschi et al., 2019).

2.2. Waste management in Iceland

Waste is managed at the municipal level in Iceland, and in the past years, the number of municipalities in the country has declined from122 in 2002 to 69 in 2021. There will be even fewer municipalities in the future as government policy aims at having 1000 inhabitants as the minimum size of any municipality (Local Government Act, 2011). The policy is based on the belief that larger municipalities can serve their residents more efficiently than smaller ones, as they will enjoy some economies of scale.

Iceland is often divided into eight regions rather than individual municipalities, which are displayed in Fig. 1. Municipalities are not evenly distributed among the eight regions; five out of the eight most populous municipalities are located in the Capital Region, and another two within a 50 km radius of the capital. The only large municipality not in southwestern Iceland is Akureyri in the northeast, 250 km in a straight line from the capital, right through the centre of the island, or 390 km by road.

Although Iceland is a well-developed economy and thus similar to many neighbouring countries, three characteristics make international comparison on waste management difficult. First, Iceland is in essence a city-state, with two thirds of the nation residing in the Capital Region. Second, as in other norther countries, lack of infrastructure, long distances and low population density, especially in rural areas, distinguish Iceland from most comparable countries, Third, waste management strategies in most municipalities are influenced by access to affordable hydropower electricity and geothermal energy, with 90% of heated space in Iceland using geothermal energy (National Energy Authority, 2020). Waste-to-energy has therefore not been worthwhile as a method for waste disposal, unlike in many other countries. In addition to these differences, an intercountry comparison is challenging due to Iceland's lack of quality data.

Over the last five decades, waste treatment in Iceland has developed from a largely unregulated activity provided by the municipalities to a highly regulated industry. Inter-municipal cooperation has become the norm, with services carried out by publicly- or privately-owned companies having an increased emphasis on recycling and recovery. In recent years, a few thousand tonnes of MSW have been exported abroad for incineration for energy recovery.

Landfilling is the primary waste management method for MSW in Iceland, and landfills are run by municipalities or through inter-municipal cooperation. All municipalities contract with private companies to collect waste from households, with the exception of Reykjavík, the country's largest municipality (Nordic Competition Authorities, 2016).

As of 2021, 17 landfilling sites and one waste incinerator that accepts MSW are in operation (see Fig. 1 and Table 2). The maximum amount of MSW that can be landfilled, according to operating licences from 2021, is 128,080 tonnes (see Table 2), and about 12,000 tonnes can be incinerated annually. Before 2021, the annual amount of MSW was up to 171,080 tonnes per year; however, landfill sites often exceed their limits. For instance, the amount of MSW landfilled or incinerated in

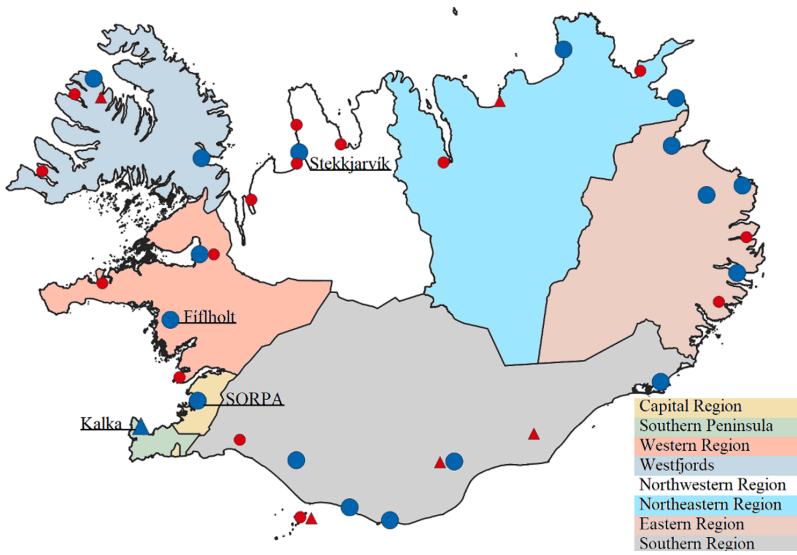


Fig. 1. Regions of Iceland and locations of operating and decommissioned (from 2009 to present) landfilling sites and incinerators for MSW. Landfills are marked with a circle and incinerators with a triangle. Operating sites are in blue and decommissioned sites smaller and in red. Map details from the National Land Survey of Iceland https://www.lmi.is.

Table 2
Operating landfilling sites and maximum amount of MSW that can be landfilled according to the operating licence in 2021.

Name	Latitude, longitude	Maximum amount of landfilled MSW	Validity period of operating licence
Capital Region			
SORPA–Álfsnes	64°11′16.2″N 21°44′42.0″W	77,000	31.12.2023
Western Region			
Fíflholt	64°41′44.6″N 22°08′37.6″W	15,000	5.2.2028
Höskuldsstaðir	65°06′56.1″N 21°40′31.5″W	500	9.9.2027
Dalabyggð			
Westfjords			
Hóll Bolungarvík	66°09′12.9″N 23°15′43.6″W	500	20.8.2035
Skeljavík við	65°40′55.6″N 21°41′30.9″W	500	10.7.2028
Hólmavík			
Northwestern Region			
Stekkjarvík	65°43′00.2″N 20°16′14.6″W	21,000	26.11.2026
Northeastern Region			
Kópasker, Viðarás	66°19′29.0″N 16°25′20.7″W	500	16.12.2031
Bakkafjörður í	66°02′20.6″N 14°47′09.8″W	200	21.03.2034
Langanesbyggð			
Eastern Region			
Búðaröxl	65°45′22.0″N 14°51′01.3″W	1,000	16.12.2031
Vopnafjarðarhreppur			
Tjarnarland á	65°27′37.3″N 14°20′34.8″W	2,500	8.7.2031
Héraði			
Brandbalar	65°31′02.9″N 13°49′16.6″W	200	20.3.2036
Borgarfjarðarhrepp			
Þernunesi	64°59′07.4″N 13°53′48.0″W	3,000	6.2.2036
Reyðarfirði			
Southern Region			
Melur í landi Fjarðar	64°18′27.6″N 15°00′35.4″W	3,000	6.11.2028
Hornafirði			
Stjórnarsandur,	63°48′02.6″N 18°00′48.8″W	200	27.11.2029
Skaftárhreppi			
Uxafótarlækur,	63°25′15.7″N 18°56′58.0″W	80	1.6.2026
Mýrdalshreppi			
Skógasandur,	63°30′17.9″N 19°32′08.6″W	400	14.2.2030
Rangárþingi eystra			
Total amount of MSW to be landfilled		128,080	

2019 was 144,000 tonnes.

The three largest landfilling sites of SORPA, Stekkjarvík and Fíflholt account for around 90% of the landfilling capacity for MSW (The Environment Agency of Iceland, 2021b). As in other Nordic countries, the number of landfill sites has been decreasing. Since 2009, at least 15 operating landfilling sites and five waste incinerators have closed down in Iceland (see Fig. 1), primarily because they could not fulfil the requirements of new regulations. All the decommissioned sites were outside the capital area; hence, waste from the affected municipalities must now be driven in trucks to one of the remaining landfilling sites, often hundreds of kilometres on small roads not built for the sort of traffic, leading to a deterioration of roads, rise in CO_2 emissions and increased pressure on the environment. For example, waste from Ísafjörður in the northwest must be driven close to 350 km to the landfilling site Fíflholt in the west (adding up to around 700 km driven for each landfilling event). Prior to 2010, the waste from Ísafjörður was incinerated on-site without proper air pollution management. The incinerator was closed following the implementation of modern pollution prevention guidelines and was not deemed cost-effective.

SORPA, which is located on the outskirts of Reykjavik and operates the largest landfill in Iceland, is a municipal association that handles waste in the capital area. SORPA had a permit to landfill 120,000 tonnes in 2020, which was reduced to 77,000 tonnes in 2021. Further reduction of the permissible amount of waste landfilled will occur in 2022 when it will be reduced to 38,000 tonnes. Furthermore, the filling site must close by the end of 2023 (The Environment Agency of Iceland, 2021b). By that time, GAJA, SORPA's new biogas and composting plant, which opened in 2020, should be treating up to 40,000 tonnes of organic household waste, thereby reducing landfilling needs in the area. It is unclear how it will be possible to reduce the amount of waste, enough for the above situation to be realised. Moreover, time is running out to build an infrastructure for a new incinerator or recycling facility. A temporary solution could be an increased export of waste for energy recovery or extending the operating licence of SORPA. The second-largest landfill site is in Stekkjarvík, owned by Norðurá bs, a municipal association in the Northwestern Region of Iceland. It has permission to landfill up to 21,000 tonnes, with most of the waste coming from Iceland's Northeastern and the Northwestern Regions. The third-largest landfill is Fíflholt, owned by the municipal association in the Western Region of Iceland, with the permission to landfill up to 15,000 tonnes of waste each year. Waste from the Westfjords and the Southern Region, in addition to waste from the Western Region, is landfilled there. Both Stekkjarvík and Fíflholt have applied for permits to increase their landfilling, where Stekkjarvík has filed in for 30,000 tonnes and Fíflholt for 25,000 tonnes (Stekkjarvík, 2019, Sorpurðun Vesturlands hf., 2020b). This is in part to accommodate the waste that needs to be landfilled after SORPA's landfilling site is closed down. Other landfilling sites in Iceland have an average permit of around 1000 tonnes, ranging from 80 to 3000 tonnes (see Table 2) (The Environment Agency of Iceland, 2021b).

Kalka, the sole waste incinerator in the country, is located in the southern peninsula. It can incinerate approximately 12,000 tonnes of waste per year. Most of the incinerated waste is MSW from the southern peninsula, although waste that requires incineration from other parts of the country, such as hospital waste, is treated in Katla (The Environment Agency of Iceland, 2021b). Kalka does not incinerate with energy recovery and is in an area with plenty of geothermal power.

The proportion of waste incinerated in Iceland is small compared to other nations in Europe, or less than 10% of MSW in recent years compared to around 30% in the EU (Eurostat, 2022a). The low incineration rate is partly the result of affordable access to geothermal energy and electricity from hydropower and geothermal plants and easy access to landfills. In a few villages in Iceland without access to geothermal energy, small incinerators used to be employed to provide energy or heat. For instance, in Kirkjubæjarklaustur, in the Southern Region, the local school and swimming pool were heated with energy from a small incinerator located on-site (Úlfarsson, 2013). The incinerator did, however, not fulfil modern standards and was closed at the end of 2012 due to dioxin pollution. As it was too expensive for the municipality to modernise its incineration, energy recovery was not a feasible option, since then, some of the waste has been landfilled in Fíflholt, some 350 km away by road.

Changes in waste management rules, including the 10% landfilling target by 2035 for MSW, have forced the Icelandic authorities to start exploring the feasibility of building one or more incinerators with energy recovery to reduce landfilling (Guðmundsdóttir et al., 2020, Ingasson, 2021).

3. Data

The analysis presented in this paper is based on data from Eurostat

(Eurostat, 2022a, Eurostat, 2022b), the Environment Agency of Iceland (https://www.ust.is), the Icelandic Association of Local Authorities (2021) and Statistics Iceland (https://hagstofa.is). Data from Eurostat are used when comparing waste generation and management in Iceland, the EU-27, and the Nordic countries. Data analysis of waste management expenditure and fees in Iceland is based on the Icelandic sources.

Even though waste management has been a highly regulated industry in recent times, official data in Iceland on waste are often based on estimates, and detailed data can be hard to get hold of, if they even exist. Data recording and collection in Iceland did not start systematically until around 1990, and both collection methods and details collected have changed substantially in the years since. The data until 2004 are mainly rough estimates (Meyles, 2006) based on data from Iceland's largest waste collector, SORPA, which handles waste from over 60% of the population in Iceland. Legislation from 2003 (Waste Management Act, 2003) requires the submission of detailed data about the type and amount of waste handled. Because of this, data have gradually improved since 2004, and in 2014 the European Waste Classification for Statistics (EWC-Stat) was implemented. Since the implementation of the EWC-Stat, the data quality has improved from year to year. While legislation on data submission has been in place since 2003, adequate data reporting was at first not highly prioritised. Although the data has improved since 2014, the quality is still not up to standards. The new policy of the Minister for the Environment and Natural Resources highlights the data quality issue, especially at the municipal level, improved waste management data high on the agenda (Ministry for the Environment and Natural Resources, 2021). When evaluating and comparing Icelandic waste data, especially before 2014, one should be aware of these data quality issues. Indeed, some reports using data from Iceland address them specifically (Papineschi et al., 2019, Guðmundsdóttir et al., 2020).

Yet another issue for academic studies on waste management in Iceland is the lack of data for different regions and municipalities, making comparisons difficult. The data used by Guðmundsdóttir et al. (2020) is, for instance, incomplete and based on rough estimates of quantities and management methods, therefore providing limited insight into the actual situation. Data on waste management fees and costs do however exist and can provide valuable insights into the situation. As municipalities are responsible for waste management, they do not receive any financial support from the government. Instead, the municipalities usually charge each household for waste management along with other taxes. Waste management fees vary between municipalities and should, in theory, cover all domestic waste management costs. However, this is rarely the case, and municipalities are therefore forced to finance the, a deficit by some other means. The annual accounts of the Icelandic Association of Local Authorities provide information on revenue from waste management fees and costs of waste management.

4. Results and discussion

4.1. International comparison

As discussed in Section 2.3, Iceland is a sparsely populated island where waste must often be transported over large distances. This fact, coupled with the lack of quality data, makes all comparisons between Iceland and other countries challenging. In 2019, the total amount of waste generated in Iceland was about 1,114,000 tonnes, and the MSW generated was about 237,000 tonnes, approximately 4% less than in 2018 but around 82% more than in 2000. At the same time, GDP increased 75.8%, or 37.4% per capita, and population size increased 28%. Hence, MSW per capita was 664 kg in 2019 compared to 462 kg in 2000, indicating a 43.7% increase.

Comparison with the EU-27 and the other Nordic countries reveals that the amount per capita of MSW generated in Iceland is only less than that in Norway and Denmark (see Fig. 2). MSW per capita increased gradually in Iceland until a sudden drop in generated waste was noted in 2007/2008, coinciding with the economic crisis in 2008. This was followed by a gradual increase in waste generated in Iceland but with a greater proportional increase over the last few years compared to other countries. The most recent data from Iceland suggest that the MSW generation per capita is declining again, although these data have not been published in the Eurostat database yet. Fig. 2 also clearly shows a sharp increase in MSW generated in Norway in 2016, which is most likely due to a change in how MSW is defined since there are no significant differences in the total amount of waste generated that year.

All Nordic countries other than Iceland have already reached the 10% landfilling target rate for 2035, as seen in Fig. 3a. Moreover, the EU-27 countries reduced landfill rates from 54% in 2000 to 24% in 2020. However, Iceland is still far from reaching this target by 2035. The landfilling rate in Iceland has only fallen by 10% in the last 20 years but must drop over 50% within the next 15 years to meet other EU targets (Fig. 3a). Based on a simple regression trendline, Iceland will only achieve the 10% target in 2070, assuming a constant change in landfilling rate.

Overall, Iceland is lagging behind most European countries and all Northern and Western European countries in reaching landfilling targets (Fig. 3a). However, as in other countries, there has been a decrease in the number of landfill sites and legal capacity in recent years, as a direct consequence of environmental concerns and changes in regulations.

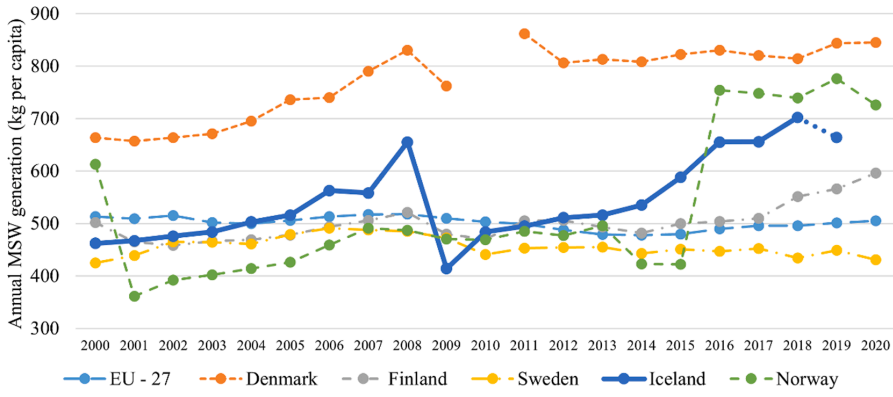


Fig. 2. Annual MSW generated in kg per capita in the Nordic countries and EU-27 from 2000 to 2020. Data source: Eurostat, (2022a), (ENV_WASMUN). Data for Iceland prior to 2018 are from Eurostat (2019); data for Iceland are based on data from the Environment Agency of Iceland (2021a).

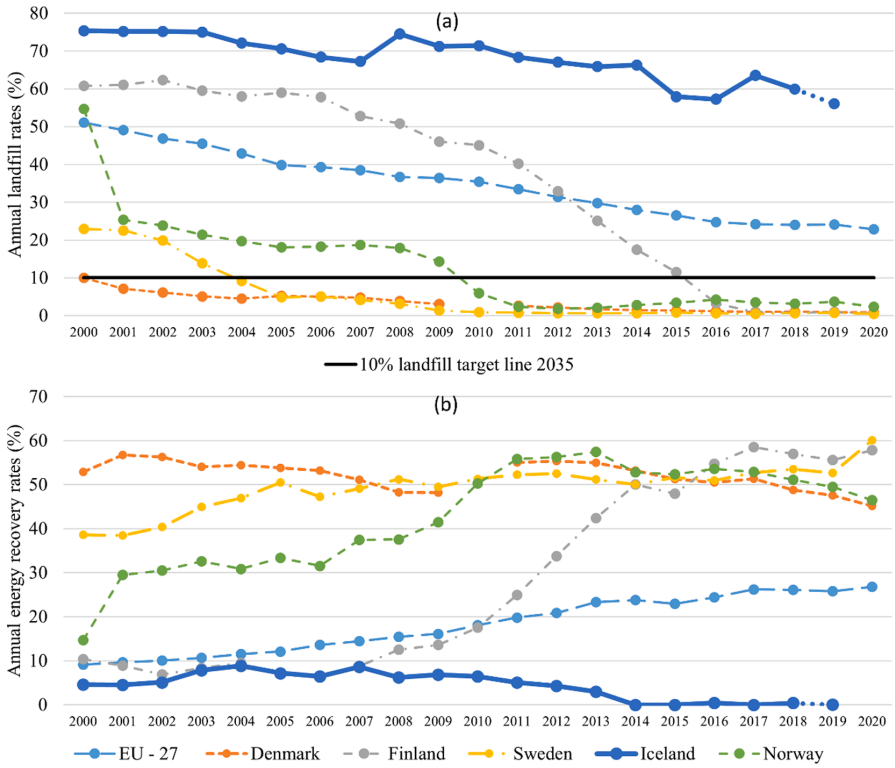


Fig. 3. Annual MSW landfill rates (a) and energy recovery rates (b) in Nordic countries and EU-27from 2000 to 2020. Data source: Eurostat, (2022a), (ENV_WASMUN). Data for Iceland prior to 2018 are from Eurostat (2019); data for Iceland are based on data from the Ministry for the Environment and Natural Resources (2021).

Currently, landfilling capacity is not distributed in accordance with population density around the country. Only 60% of the landfilling capacity is within a 50 km radius of the capital, where around 80% of the population resides, and the only landfill site in the Capital Region will be closed by 2024.

One reason for the high landfilling rate in Iceland is that energy recovery through incineration has not been cost-effective, and is therefore almost non-existent (Fig. 3b). Concurrently, the other Nordic countries have energy recovery rates of around 50% and above, and this rate has additionally increased from 10% in 2000 to 27% in 2020 in the EU-27. Fig. 3 shows that when the landfilling rate goes down, the energy recovery rates go up, which can be seen well in Finland. Iceland is an exception to this rule, where both landfilling and energy recovery have decreased, mostly due to an increase in recycling.

Building new incinerators could be one way of compensating for the loss of landfilling capacity and increasing the energy recovery rate, which is currently non-existent. A recent report for the Environment Agency of Iceland (Guðmundsdóttir et al., 2020) looked at the costs and benefits of incineration in Iceland. One of its conclusions was that there were certain benefits to continuing with a single waste incinerator in the country, near the Capital Region. First, it would be close to where most burnable waste is produced (the Capital Region produces around 73% of all burnable waste). Second, there would be a lower cost per tonne of waste for a large plant (the authors of the report did not specify who would benefit from the lower cost). However, it was also concluded that there were certain benefits to having multiple smaller incinerators throughout the country. Waste would, for instance, not have to be driven long distances, adding to cost and environmental impact. Additionally, the energy produced could increase energy security and heat houses where geothermal energy is unavailable, especially in remote places. Finally, since the municipalities can better estimate energy and incinerator needs accurately, cost and cost reductions can be spread more equitably. These arguments need to be considered carefully due to the costs of building new incinerators. While energy recovery could return some of the costs, there is much cheaper energy available in Iceland. However, energy recovery is far more cost-effective than simple incineration and will not only fit into the reuse and recycling targets of the EU but also solve some of the problems associated with the closing of landfills.

Another way to decrease the landfilling rates is to increase recycling rates. Iceland has far lower recycling rates than the Nordic and EU-27 countries, as shown in Fig. 4, although data from Iceland is very patchy. No country has so far reached the 2035 target of over 65% of total MSW recycled. However, the EU-27 countries, and Denmark and Finland individually, have hit the 65% recycling rate of packaging target set for 2025. While Sweden had reached the target in previous years, the recycling rate seems to have gone down in 2020. Overall, there has been an improvement in recycling in Iceland in the past two decades, although there seems to have been some regression in the last couple of years. Based on a linear trendline, Iceland will only reach the 65% target line for the MSW recycling rate in 2075.

4.2. Comparison between Icelandic regions and municipalities

Any comparison between municipalities regarding waste management and costs is made difficult by the lack of available data. Yearly data

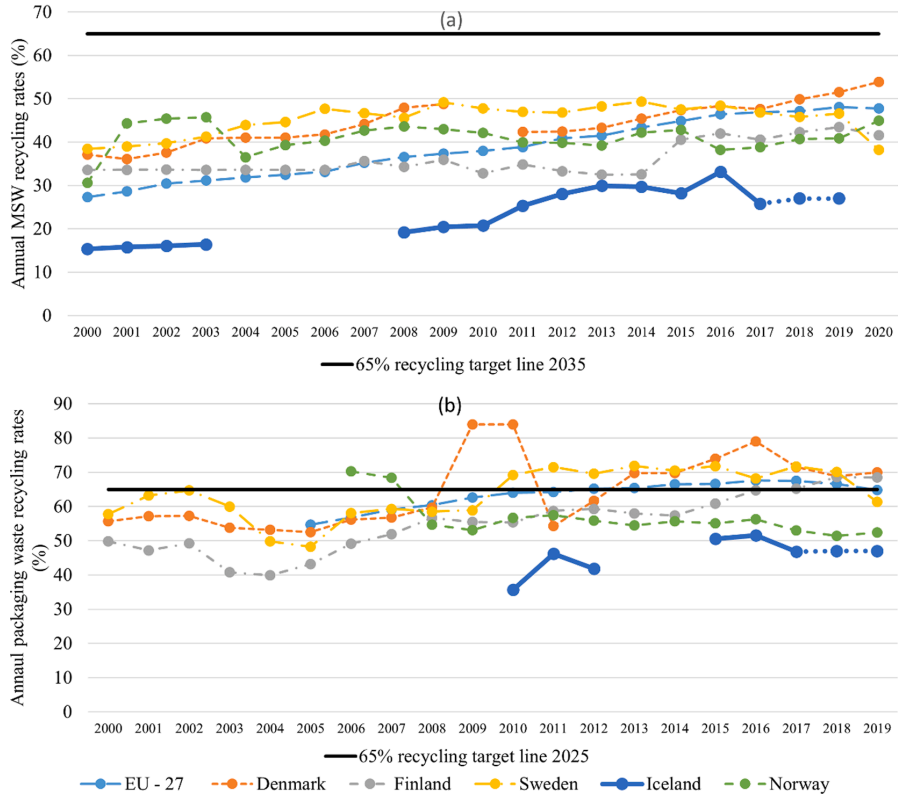


Fig. 4. Annual recycling rates of MSW (a) from 2000 to 2020 and packaging waste (b) from 2000 to 2019 in Nordic countries and the EU-27. Data source: Eurostat (2022b) (ENV_WASMUN), Eurostat (2022b) (ENV_WASPAC). Data for Iceland prior to 2018 are from Eurostat (2018), and 2019 data for Iceland are based on data from the Ministry for the Environment and Natural Resources (2021).

on the amount of waste in each region or municipality is unavailable, and the data used in Guðmundsdóttir et al. (2020) for the year 2018 was not provided for use in this study. From the Guðmundsdóttir et al. (2020) report, it is possible to obtain a rough estimate of how the total amount of waste in Iceland is divided between the regions, and how the composition differs. The total amount of waste and its composition are roughly distributed, according to the distribution of the population and heavy industries. The size and population density of the municipalities and their economic standing vary considerably, and due to the lack of data on direct waste quantities and management, the only way to compare waste management between municipalities, based on currently available data, is in the context of expenditure. Therefore, cost of waste management per capita was used to compare MSW management in Iceland between municipalities and regions, from the year 2002 to 2020. Fig. 5a shows that the cost differs considerably between regions, and that the cost has increased substantially in recent years in some areas. The expenditure has increased much more in regions with fewer inhabitants and lower population density than in other regions. The cost per capita is lowest in the Capital Region, the Southern peninsula and the Western Region. These are notably two out of the three regions with large landfills and the region with the only incinerator (see Fig. 1 above). In the capital area, where most inhabitants live and the largest landfill site is found, the cost per capita (in 2021 ISK prices) was almost the same in 2020 as in 2002 (7.8% increase). At the same time, the increase in waste management cost per capita in the Westfjords and the Southern region was around 124%.

In 2020, there were 69 municipalities in Iceland; annual accounts from all of them are available, but only 64 contain information on the waste management cost. Of the 64 municipalities, eight municipalities had greater than 10,000 inhabitants in 2020, 23 had 1,000 to 10,000 inhabitants, and 33 had fewer than 1,000 inhabitants. The results show that the average per capita waste management cost in municipalities with greater than 10,000 inhabitants was around 16,000 ISK (€106 with reference rate EUR 1 = ISK 150) compared to 30,500 ISK (€203) for municipalities with 1,000 to 10,000 inhabitants and 56,900 ISK (€379) for municipalities with fewer than 1,000 inhabitants. The cost of waste management in municipalities with 10,000 inhabitants or more has changed very little since 2002, with about a 10.8% increase (Fig. 5b). For municipalities with 1,000 to 10,000 inhabitants, the cost per capita has increased by about 64%, and for municipalities with fewer than 1,000 inhabitants, the reported waste management cost has increased by 140% since 2002. The difference between the largest municipalities and the smaller ones is statistically significant for every year. The difference between municipalities with 1,000 to 10,000 inhabitants and with fewer than 1,000 has been significant since 2003, and between municipalities with 1,000 to 10,000 and those with over 10,000 inhabitants since 2008 (Mann–Whitney *U* test: max p-value 0.022).

One factor in this differing cost between municipalities is the closing of landfills and incinerators in rural areas in the period studied (see Fig. 1). Act 55/2003 specified new and stricter regulations for landfilling that had to be fulfilled before 2009, or else the landfilling sites would have to close. Consequently, the cost of operating the landfilling sites went up, and tipping fees for the remaining landfilling sites increased. This also meant higher transportation costs for many municipalities far

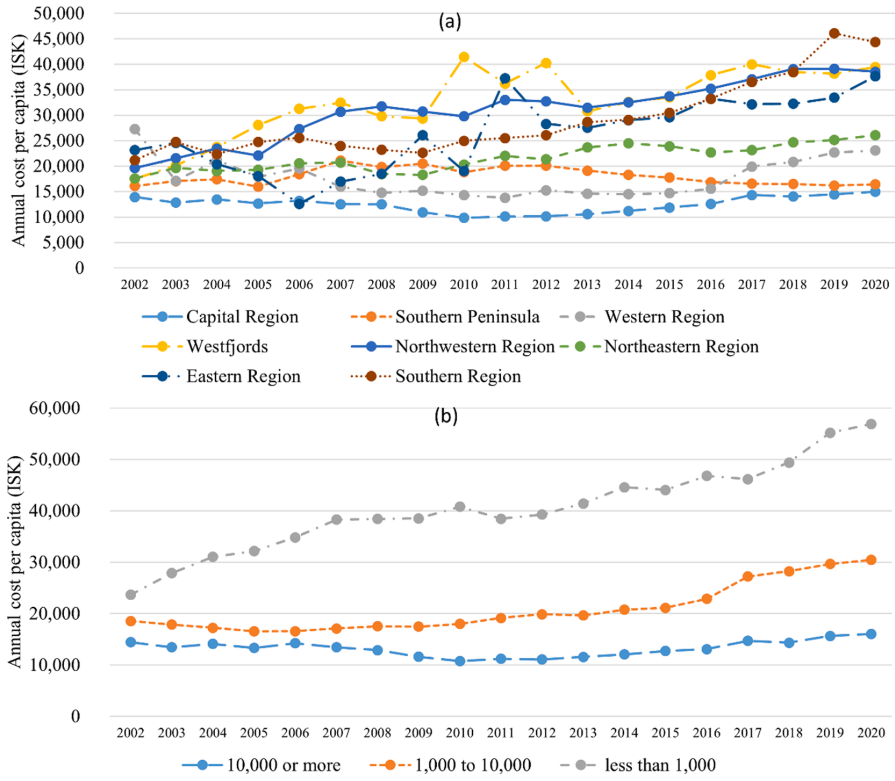


Fig. 5. Annual municipal cost per capita in the Icelandic regions and municipalities by population, according to municipal annual account information 2002–2020 (In ISK at 2021 prices). Data from Icelandic Association of Local Authorities (2021).

from the remaining landfilling sites, although there is no data for the exact amount municipalities have had to spend on the transport of MSW. However, just in 2019, 3,161 tonnes of waste from the Westfjords and 2,184 tonnes from the Southern Region, previously landfilled on site, had to be landfilled hundreds of kilometres away in Fíflholt in Western Iceland (Sorpurðun Vesturlands hf., 2020a).

Each municipality decides how much they charge for waste management fees, and this fee can vary considerably between municipalities. There are two ways municipalities can charge their fees: a flat rate on real estate units and/or base the fee on the amount of waste, type of waste, discharge frequency, waste disposal and other factors that can affect the costs.

The difference between the cost and the charged waste management fees in Fig. 6a shows that most regions are spending more on waste management than they are charging. The deficit in the Capital Region and Southern peninsula has been close to zero since 2010. Other regions have been spending on average around 10,000 ISK (€67) more per capita than they have been charging in fees, an amount covered by municipal taxes. It is also notable that the North-western Region, where the second-largest landfilling site is located, is subsidising waste management far more than the other regions (around 18,000 ISK(€120)). Waste management fees in each municipality are a political decision, and the subsidising costs may therefore be traced to a political decision made by elected officials.

Fig. 6b shows that municipalities with fewer than 1,000 inhabitants have the largest deficit, with each paying, on average, over 17,000 ISK (€113) more per capita for waste management than they are charging. Conversely, the biggest municipalities have had close to zero deficit since 2011. The difference between the municipalities with fewer than 1,000 inhabitants and others has been statistically significant since 2003. The difference between municipalities with 1,000 to 10,000, and those with over 10,000 inhabitants was statistically significant in the periods 2008–2012 and 2015–2020 (Mann–Whitney *U* test: max p-value 0.038). The results show increased expenditure in smaller municipalities, while the cost for bigger municipalities has remained nearly the same.

4.3. Policy implications

As shown above, the municipalities outside the Capital Region, especially the smaller ones, spend considerably more on waste management than the larger communities. The fees that Icelandic municipalities currently charge residents should cover waste management costs, although they often do not, leaving municipalities to cover the difference on their own. Moreover, waste management cost is rapidly increasing and is expected to increase further due to more stringent waste management targets, including the target to landfill less than 10% of MSW by 2035. In addition, under the new waste management policy, the municipalities are required to charge fees that cover the cost of waste management in its entirety (Ministry for the Environment and Natural Resources, 2021). This means that in order to live up to promises made by the Icelandic government, Icelanders living in smaller, more remote municipalities will, in some cases, have to annually pay tens of thousands of ISK more in waste management costs than Icelanders living in the Capital Region.

Fulfilling regulations and national commitments in time without any assistance from the government could severely impact people's willingness and ability to live in small and isolated municipalities – an

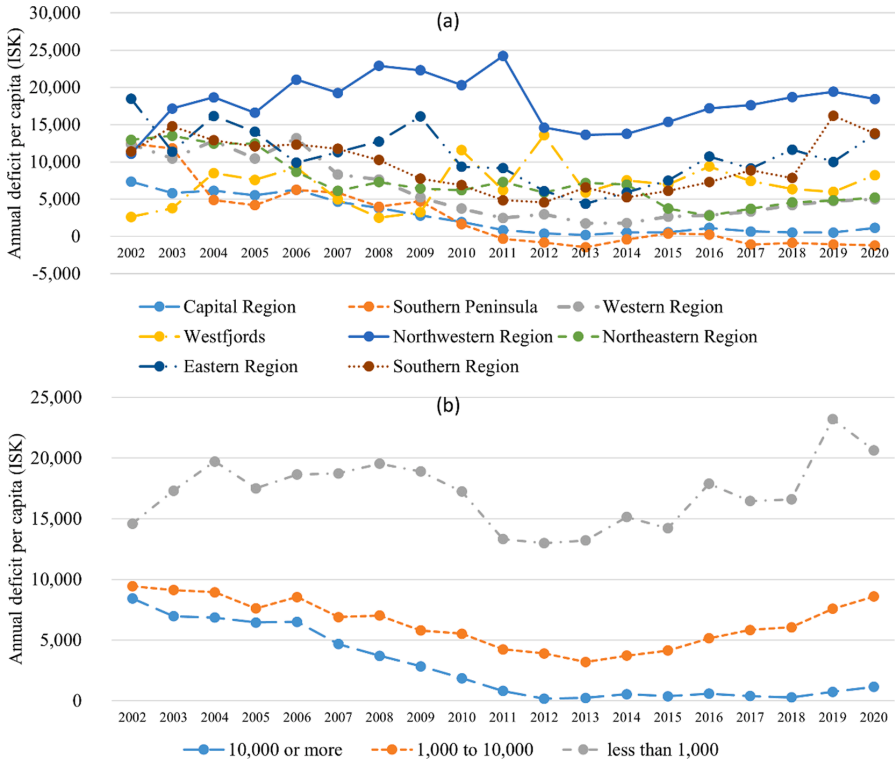


Fig. 6. Annual deficit of municipal cost per capita 2002–2020 in the Icelandic regions (a) and municipalities by population, according to municipal annual account information (b) (In ISK at 2021 prices). Data from Icelandic Association of Local Authorities (2021).

unintended consequence of more stringent regulations. To react to the possibility, the government has at least two mitigating options: to postpone the enactment, for example, of the more stringent target of the landfill directive, or to provide financial assistance to smaller municipalities.

According to the Amendments to the Landfilling Directive (EU 2018/850) (European Commission, 2018a) article 5(6), Iceland can postpone the 10% landfill deadline to 2040. Additionally, EU directives 2018/851 and 2018/852 allow for the postponing of deadlines up to five years before the targets are set there. By postponing the deadlines, Icelandic municipalities could spread the cost of reaching these targets over a longer period. While it is possible to apply for the landfilling extension up to two years before 2035, the level of infrastructure and planning needed, especially by smaller municipalities, means that costs could be reduced considerably with a longer adjustment time. The possible exemptions for isolated settlements from directive 1999/31/EC (European Commission, 2018d), as stated in article 3(4), could reduce waste management costs in the isolated settlements, thereby allowing them to have more lax waste management regulations due to the exemptions. While this would alleviate some financial burden on smaller municipalities, this policy change would undoubtedly not be a feasible long-term solution due to the continued risk of pollution from waste and waste accumulation.

The government of Iceland currently does not provide any financial assistance to remote municipalities to help them fulfil legal requirements according to national commitments. In many other countries, governments provide subsidies and grants to level the playing field for municipalities. For instance, in Canada, the municipalities within Newfoundland and Labrador are responsible for waste management on the ground level, such as waste collection and landfills following the Provincial Waste Management Strategy, under the supervision of the provincial government (Fang et al., 2018). The provincial government assists municipalities in offsetting costs associated with the changed waste management practices required by the government. Additional policies are set by the federal government, which provides financial assistance through programmes such as the Green Municipal Fund and the First Nations Waste Management Initiative. The current law on regional policy mandates equals opportunities and standards of living (Regional Planning and Development Plans Act, 2015). Following the example of other nations, the Icelandic government could consider providing financial assistance, based on the different and escalating costs of waste management in smaller isolated municipalities, and thereby enable all municipalities to reach national targets in time. While this could reduce the costs faced by smaller municipalities on paper, it is likely that the increased cost placed on the government would lead to increased taxes and indirect costs for affected municipalities.

Whether the Icelandic government will provide some financial assistance to the most affected municipalities or postpone some of the deadlines of the EU targets and file for exemptions for isolated settlements remains to be seen, but without any intervention, there is the risk of rural exodus and abandonment of small settlements and farm areas. The government aims to increase sustainability and implement a change to a circular economy, which means more emphasis on recycling and reusing and techniques to utilise waste. Methods for MSW management, such as composting and production of methane and biofuel, have been on the rise in the last few years, and these are products used by the municipalities to alleviate costs of disposal. However, new treatment methods often require a high start-up cost that municipalities may not be

able to recoup before the methods are made obsolete, due to the small amounts of waste generated. For some reason, Iceland seems to be singularly focussed on incinerators with energy recovery in the future (Guðmundsdóttir et al., 2020, Ingasson, 2021) rather than other techniques.

5. Conclusions

It is clear that if the government of Iceland intends to achieve the goals it has committed to, a major overhaul of MSW management strategies, recycling and waste disposal culture is needed. Whilst law and policy call for a greater move towards a circular economy and sustainable waste management, no guidelines exist for them, and each municipality will have to face tough decisions following the ban on locally subsidising waste charges. Municipalities will have to consider the most cost-effective ways of disposing of waste, considering the limitations set in place by governmental regulations, and bearing in mind that higher charges may increase illegal waste disposal. Thus, the question arises whether there should be charges based on weight or volume or a fixed cost, and how public participation will be affected by either.

One of the more ambitious plans in place in Iceland is that no landfilling should take place in the future (Ministry for the Environment and Natural Resources, 2021). Considering that the landfilling rate has only gone down around 10% since 2000 and still sits above 60%, this can be considered a tall order and will require substantial changes in waste management practices. Decisions must also be made on recycling policy and how charges for that should be handled, especially considering the large sums already being charged for waste management and the considerable cost inequality between municipalities. This needs to be factored in when deciding on the feasibility of building new infrastructure to help smaller municipalities.

Due to the lack of good quality historical data, it is difficult for most municipalities to develop good predictions based on past and current situations. Although a few municipalities have received some leeway from the Environment Agency of Iceland, when it comes to waste disposal, it is unclear how that has affected waste management and cost per capita, or if appropriate data is being kept that would allow other municipalities to justify requesting EU extensions. In the absence of state subsidies and EU extensions, Icelandic municipalities also urgently need guidance on formulating their waste management.

Finally, a discussion about the future of waste management is required, considering the development of new sorting techniques and various implementations of artificial intelligence. This is important since MSW management has, to an extent, not been economically viable and in the future, economic incentives regarding recycling and other waste disposal methods need to allow for sustainable development, especially for smaller municipalities.

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. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Evaluating municipal solid waste management efficiency in Iceland: A data envelopment analysis of socioeconomic and geographic influences

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ABSTRACT

This study aims to evaluate the efficiency of municipal solid waste management in Iceland, focusing on the factors influencing waste generation and recycling rates. Utilizing Data Envelopment Analysis (DEA) and regression techniques, the research seeks to provide insights into the challenges that municipalities face in managing waste effectively, particularly regarding their unique socioeconomic and geographic characteristics.

The analysis covers 48 of Iceland's 69 municipalities from 2019 to 2021, employing input- and output-oriented DEA models. It explores the relationship between waste management costs, solid waste per capita, recycling rates, and socioeconomic factors such as age, population size, disposable income, and rural-urban ratios.

The results reveal significant disparities in efficiency among municipalities. Larger population sizes and smaller geographical areas positively correlate with waste management efficiency, while older populations and higher waste management costs negatively impact performance. The relationship between rural populations and efficiency is complex, highlighting the influence of both population density and socioeconomic characteristics on waste management outcomes.

This research provides valuable insights into waste management efficiency in rural and Arctic regions. It emphasises the necessity for tailored strategies that consider each municipality's unique characteristics and resource limitations, advocating for targeted policies and government support to improve waste management practices and promote sustainability in Arctic and rural communities. Additionally, the findings enhance the current literature by addressing a gap in understanding waste management efficiency in remote and lesser-studied regions, thus informing both academic discussions and practical applications in policy formation.

1. Introduction

Rural areas worldwide face challenges maintaining socioeconomic and environmental stability, especially in small settlements. This trend is particularly noticeable in the Arctic region, which includes parts of the Arctic Ocean and territories within Canada, Russia, Greenland, the United States (Alaska), Norway, Sweden, Finland, and Iceland. As smaller settlements experience population decline, they become more vulnerable due to their economic dependence on natural resources, reduced social cohesion, and heightened risk of environmental degradation as a result of poor waste management practices. These challenges are exacerbated by a broader trend of urbanization, as more people move to larger urban centres in search of better economic opportunities and access to services (Kirsanova et al., 2024). The implications of these challenges affect all aspects of rural life in the Arctic, including a considerable impact on waste management practices throughout the region. The unique geographical characteristics of the Arctic, including remote locations, inadequate infrastructure, and extreme climatic conditions, complicate waste collection and disposal efforts which leads to elevated costs as well as limited participation in recycling and waste reduction programs (Sebastian and Louis, 2022; Óskarsson et al., 2022; Burns et al., 2021; Agakhaniants et al., 2019; Keske et al., 2018; Eisted and Christensen, 2011; Starostina et al., 2014). As waste management is directly linked to living conditions, public health, environmental sustainability, and economic performance, any inefficiencies in waste management systems can severely impact the quality of life in Arctic

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communities.

Globally, the importance of effective waste management cannot be overstated; waste management serves as a base for sustainable development, influencing both environmental health and economic prosperity. Poor waste management practices contribute to pollution, habitat destruction, and health hazards, while efficient systems can lead to significant economic benefits, including job creation, resource recovery, and reduced environmental remediation costs (Mahartin, 2023). The economic advantages of efficient waste management are particularly pertinent in light of the increasing global emphasis on circular economy principles, which advocate for minimising waste through recycling and resource recovery. This approach not only conserves natural resources but also creates new economic opportunities, fostering innovation and sustainable job growth in the waste management sector (Ferronato and Torretta, 2019).

Despite the pressing need for effective waste management, there has been a notable absence of comprehensive studies focusing on rural areas and the Arctic region, which this article aims to address by evaluating the efficiency of municipal solid waste management in Iceland and examining the factors that influence waste generation and recycling rates in this context. While some research has highlighted the inefficiencies of waste management practices in specific Russia's Arctic regions (Nedoseka et al., 2021) and the development of eco-industrial parks aimed at improving waste management efficiency (Liubarskaia et al., 2019), a broader analysis of municipal waste management systems in the Arctic is lacking. This gap in the literature emphasises the necessity for a thorough examination of the factors influencing waste management efficiency in this unique and challenging environment. Understanding these factors is crucial not only for enhancing waste management practices in Arctic municipalities but also for drawing comparisons with waste management systems in other regions facing similar challenges.

Iceland presents a unique case study due to its geographic and socioeconomic characteristics. The subpolar oceanic climate of Iceland results in less severe weather conditions compared to many other Arctic nations; however, the country grapples with many of the same waste management challenges, particularly those related to population distribution and size imbalances (Óskarsson et al., 2022). With an average population density of just four persons per square kilometre and approximately two-thirds of its nearly 400,000 inhabitants residing in the capital region, Reykjavik, the operational costs and logistical complexities of waste management systems in Iceland are significant. Despite being classified as an Arctic state, the majority of Iceland lies south of the Arctic Circle (66°N), although its northernmost community, Grímsey, is situated just 40 km off the coast (Arctic Council, n.d.). The waste management challenges in these low population areas are further compounded by the need to comply with European Union recycling and waste reduction targets, which Iceland, as a member of the European Economic Area (EEA), is obligated to meet, in part due to the costs associated with implementation.

In response to these challenges, this study aims to measure the performance of municipal solid waste generation and recycling rates in Iceland using two Data Envelopment Analysis (DEA) models; first a two-stage DEA model, where a second-stage regression is used to determine how the calculated efficiency scores are impacted by socioeconomic (population, mean age of inhabitants, and per capita income) and geographical variables (size and rural-urban ratio), and then a standard DEA model where the variables used in the second stage regression of the first model are included as inputs. DEA is a robust non-parametric method based on linear programming introduced by Charnes et al. (1978) which has been widely applied across various sectors, including healthcare, education, and government services, to assess efficiency (Miencha et al., 2017; Narbón-Perpiñá & De Witte, 2018a, 2018b). Recent studies have also employed DEA to analyse waste management efficiency at both national and local levels, with notable works evaluating the environmental and circular economy performance of multiple European countries (Giannakitsidou et al., 2020) and creating waste management composite indices based on circular economy performance (Milanović et al., 2022). Analyses using DEA have further expanded the understanding of waste management efficiency across different regions, including municipalities in Czechia (Struk and Boďa, 2022), Flanders (Rogge and De Jaeger, 2012), Italy (Sarra et al., 2017; Ferraro et al., 2023), Portugal (Amaral et al., 2022; Moraes e Soares, 2024), Chile (Doussoulin and Colther, 2022; Molinos-Senante et al., 2023), and Mexico (Salazar-Adams, 2021). Among the researchers who have applied a second-stage DEA in their research are Sarra et al. (2017), Salazar-Adams (2021), and Struk and Boďa (2022).

Despite the wealth of research conducted in other contexts, the Arctic remains under-explored in terms of waste management efficiency analysis. This study seeks to fill that gap in the literature by conducting a Data Envelopment Analysis of waste management efficiency in Iceland using data from 48 Icelandic communities from 2019 to 2021. The novelty of this study lies in its analysis of waste management efficiency in a small economy located in the Arctic region, with vast rural areas. The findings aim to enhance the understanding of waste management practices in Iceland and provide local governments and policymakers with valuable insights into the factors that influence waste management efficiency. Furthermore, this research seeks to inform the development of strategies that can improve waste management systems in Iceland and other rural and Arctic regions facing similar challenges, promoting a more sustainable and economically viable future for these communities.

2. Background

Waste management in Iceland has remarkably improved over the past fifty years, transitioning from a primarily unregulated system managed by municipalities to a highly regulated industry (Óskarsson et al., 2022). Before 1970, waste disposal methods primarily involved dumping refuse into the ocean, incineration, or landfilling. Over the subsequent two decades, there was a shift towards more stringent practices in line with other developed nations that increasingly utilized landfilling and burning waste in controlled open pits (Meyles, 2003). Iceland's first pollution control regulation came into effect in 1990, coinciding with the establishment of the Ministry of Environment. Since then, there has been a growing emphasis on integrating the concept of sustainable development and climate change mitigation, highlighting the importance of protecting the Iceland's ecosystems. Additionally, Iceland joined the European Economic Area (EEA) on January 1, 1994, which led to the development of waste management practices that promote recycling and reduce landfilling to bring a greater alignment with common practices throughout the EEA. Iceland now operates under a regulated framework that emphasises a waste hierarchy: prevention, reuse, recycling, recovery, and disposal as a last resort. The alignment of Iceland's waste management practices with the United Nations Sustainable Development Goals reflects a broader commitment to environmental sustainability and social responsibility. Specifically, Goal 12, which aims to ensure sustainable consumption and production patterns, is particularly relevant to Iceland's waste management framework (Ministry for the Environment and Natural Resources, 2021).

As a member of the EEA, Icelandic authorities are committed to adhering to EU directives on waste and achieving recycling and waste reduction targets. They have incorporated the EU's directives into Icelandic legislation, with the last significant change coming into effect on January 1, 2023 (Waste Management Act, 2021). As shown in Table 1, Iceland still lags far behind most EU targets for solid waste management. Besides the law, Iceland's government has set forth an ambitious policy to implement substantial changes to waste management by enhancing sustainability, thereby accelerating the transition towards a circular economy. Furthermore, the government has set a goal to eliminate landfills (Ministry for the Environment and Natural Resources, 2021).

In Iceland, approximately 1.3 million tons of waste were generated in 2021, with municipal solid waste accounting for about 19 % (246,000

Table 1
EU targets for recycling for the Years 2025, 2030, and 2035, and the situation in Iceland in 2021.

	EU targets		Iceland	
Year	2025	2030	2035	2021
Waste diversion through reuse and recycling	55 %	60 %	65 %	26 %
Packaging waste	65 %	70 %		57 %[a]
Plastic	50 %	55 %		27 %
Wood	25 %	30 %		82 %
Ferrous metals	70 %	80 %		23 %
Aluminium	50 %	60 %		91 %
Glass	70 %	75 %		0 %
Paper and cardboard	75 %	85 %		82 %

[a] 2020 value. (European Commission, 2018b, 2018c, 2018d). Icelandic data are based on ENV_WASPACR last update: 21/03/2023 22:00 and https://urgangur.is/maelabord/.

tonnes) which corresponds to approximately 660 kg per capita (The Environment Agency of Iceland, 2023), which is similar to the average municipal solid waste generation in the Nordic countries but higher than the European union average of 533 kg per capita (Statistics | Eurostat, n.d.). In most instances, the origin, composition, and treatment of the waste are known. Although much of the waste is collected for recycling or recovery, a significant amount still ends up in landfills. Iceland's landfill rates are much higher than those in Nordic countries and the EU average, according to Óskarsson et al. (2022). In 2021, around 170,000 tons of total waste was landfilled, of which 56 % was municipal solid waste, amounting to about 98,000 tons (The Environment Agency of Iceland, 2023). Table 2 details the handling of municipal solid waste in Iceland for the year 2021, presenting quantities and proportions for disposal, recycling, and recovery.

Incineration with energy recovery has been a prominent method for managing municipal solid waste in other Nordic countries; however, its implementation in Iceland has been limited, as due to the abundant availability of affordable hydropower and geothermal energy resources, the economic viability of waste-to-energy solutions has been constrained (Óskarsson et al., 2022). Currently, the country operates only one incinerator, which has a processing capacity of approximately 12,000 tonnes per year. Consequently, the volume of waste incinerated in Iceland remains minimal, representing less than 10 % of the total waste generated. In the past, there were more incinerators, but they were generally small and did not fulfil standards regarding pollution, so they were closed. Various stakeholders, including the Ministry of the Environment, Energy and Climate, municipalities, and local organizations in southern Iceland, have though initiated analyses and evaluations concerning establishing a high-tech incineration facility. This proposed plant aims to divert waste from landfills and enhance the country's waste management strategies (Hátæknibrennslustöð, n.d.; Ingason, 2024). In recent years, there has been a notable increase in the export of waste for energy recovery through incineration. For instance, while waste exports were nearly non-existent in 2018, projections indicate plans to export over 40,000 tonnes in 2024 (Sorpa, 2023). This export is primarily due to the largest landfill site in Iceland, located in the capital area owned by Sorpa, has reduced its permitted landfill capacity. In 2020, this landfill site could handle 120,000 tonnes of waste; in 2023, it was down to 38,000 tonnes (Óskarsson et al., 2022). Although it was supposed to close at the end of 2023, the landfill has since received a dispensation to continue operating at this reduced capacity until the end of 2025.(Umhverfisstofnun | Urðunarstaður SORPU, Álfsnesi, n.d.). In the absence of infrastructure, such as high-tech incineration facilities capable of processing waste that was formerly directed to landfills, exporting waste for energy recovery has become an actual practice. This is intended to be a temporary solution. In Iceland, waste management is done at the municipal level, with municipalities contracting private companies to collect waste from households, except for Reykjavík, the country's largest municipality (Nordic Competition Authorities, 2016). The Waste Management Act (2021) applies to all municipalities in Iceland, one of its major changes being that waste collections across the country will be coordinated to promote increased waste sorting, ensuring that residents have the same number of bins at home for waste sorting throughout Iceland. Icelandic law requires that each household possess four bins for waste collection: one for paper and cardboard, one for plastics, one for bio-waste, and one for general waste. Additionally, residents are expected to sort glass, metals, and textiles at nearby recycling drop-off points. At most drop-off points, residents can drop off more types of sorted waste than just those three categories, including various types of paper, plastic, batteries, drink containers, and more. Other sorted waste is deposited by residents at their municipalities' recycling centres, such as electrical and electronic equipment, bulky waste, gardening waste, and hazardous wastes such as those containing heavy metals or organic solvents. According to Waste Management Regulation, no 803/2023 (Ministry of the Environment, Energy and Climate, 2023), bins must use an Icelandic implementation of standard Nordic labels and colour schemes.

Table 2
Amount of Municipal Solid Waste in Iceland and its treatment in 2021.

	tonnes	%
Disposal landfilled	98,044	39.9
Other disposal	5,835	2.4
Recycling	65,168	26.5
Recovery	76,607	31.2
Total	245,654	

Data from https://urgangur.is/maelabord/(June 2023).

Consequently, many municipalities have been compelled to change their waste collection and disposal methods. In the capital area and many other municipalities, the transition to a coordinated waste collection system was fully implemented in 2023, while implementation in the rest of the municipalities was scheduled for 2024. Since the introduction of this coordinated system, residents have experienced a significant increase in the financial burden associated with waste management. For instance, in Reykjavík, Iceland's largest municipality, the average cost for residents surged by 20 % in 2024 (Reykjavíkurborg, 2023). Similarly, in Fjarðabyggð, a municipality located in Eastern Iceland, residents faced an average cost increase of 35 % (Eyþórsson, 2023). The rising costs associated with waste management are not solely linked to the recent changes in regulations. Research by Óskarsson et al. (2022) indicates that, from 2002 to 2020, municipalities with populations under 1,000 inhabitants experienced a 140 % increase in waste management costs. Meanwhile, municipalities with populations ranging from 1,000 to 10,000 saw a 64 % increase, and those with over 10,000 inhabitants experienced an approximate 11 % increase during the same time frame.

The variation in waste management costs across municipalities is notable. Data from 2019 to 2021 reveal that the cost per capita for waste management differs significantly among municipalities in Iceland included in this study, with some municipalities incurring costs more than five times higher than others. A comparative analysis of the ten municipalities with the lowest waste management costs and the ten with the highest reveals that the former are predominantly urban areas, averaging less than 10 % of the area size of their higher-cost counterparts. Furthermore, these lower-cost municipalities boast populations that are over thirty times larger on average and have disposable incomes exceeding 1 million ISK (ca. 6,800 €) per annum more than the municipalities with the highest costs.

Many municipalities may face challenges in meeting recycling and waste reduction targets, particularly remote areas that may require financial assistance from the Icelandic government to fulfil national obligations—assistance that is currently lacking. The trajectory of waste management costs suggests a potential for further increases, which could lead to illegal waste disposal practices. Indications of such behaviour have already been observed in Reykjavík (Guðnason, 2024),

where individuals have been reported leaving their waste in open areas around the capital.

The municipalities vary considerably in population and size. Reykjavik, has close to 140,000 inhabitants while six other towns in the capital region have more than 10,000 inhabitants, there is only 1 other town of similar size in the rest of the country – Akureyri, located on the island's northern shore. In contrast, a little over fifty persons live in each of the three least populous communities. Þingeyjarsveit in the northeast – with a population of 1,400 – is the country's largest municipality, covering an area of 12,000 square kilometres, half the size of Sicily. At the opposite end of the scale is the municipality of Seltjarnarnes in the capital region, where 4,500 individuals reside in an area covering just two square kilometres.

In keeping with the overall trend of population decline in rural areas, the number of municipalities in the country has declined from 122 in 2002 to 64 in 2024, reflecting a trend towards consolidation in local governance. The government expects this decline to continue, believing many smaller municipalities cannot serve their residents effectively. To address this, the Local Government Act (2011) mandates a minimum population threshold of 1,000 inhabitants for municipalities, aiming to enhance the effectiveness of local services through resource unification, improved administration and more efficient municipalities.

3. Methods

3.1. Data

The data used in this study cover forty-eight out of sixty-nine municipalities from 2019 to 2021, which together accounted for 94 % of Iceland's population. The data for the remaining twenty-one municipalities either did not exist or were limited and, therefore, not included in this study. The variables used in this study are summarised in Table 3. Municipalities outside the capital area have smaller populations, and their residents tend to have a slightly higher mean age, lower incomes, and higher waste management costs than those with larger populations. They also tend to have a higher share of the rural population than the more populous municipalities.

Some of the variables used in this study align with those employed in other studies, such as cost, population, and amount of waste. For example, Struk and Boďa (2022) based their analysis on variables including municipal solid waste expenditure, population, built-up area, housing units, total waste generation, and separated waste generation. Ferraro et al. (2023) used total annual costs per capita of managing urban hygiene services as the input variable and the amount of disposed waste, categorised into sorted and unsorted waste, as the output variable. Sarra et al. (2017) based their analysis on waste costs, the amount of unsorted waste, and separated waste.

Due to the significant variations between municipalities, logarithmic transformations were applied to the population and geographical size variables and then all variables used in the analysis were range normalised (Sueyoshi and Goto, 2013) within the [1,101] range; this range was selected to avoid zero values. Finally, as the aim of waste management is to reduce the quantity of waste for a more sustainable and healthy environment, the amount of municipal waste per capita variable was reversed (Ardila Gamboa and Ballesteros Riveros, 2018; Lewis and Sexton, 2004) so that the municipality with the highest amount of waste received a value of 1, and the municipality with the lowest amount of waste a value of 101. The population variable and disposable income per taxpayer were also reversed so that the municipality with the lowest population and the one with the lowest income received a value of 101, as more populated and wealthier municipalities ought to be more efficient.

The variance inflation factor (VIF) and Pearson's correlation coefficients are used to evaluate the presence of multicollinearity among the explanatory variables (Shrestha, 2020).

The VIF ranged from 1.35 to 2.04, far lower than the value of 5, which is indicative of multicollinearity, and the absolute value of the correlation coefficient is less than 0.61, as seen in Table 4. The small values of the VIF corresponding to the variables and a correlation below 0.8 indicate no multicollinearity problem (Shrestha, 2020).

Table 3
Descriptive statistics for variable in the analyses.

	Mean	Std. Dev	Min	Max
2019				
Waste management cost per capita (ISK thousands)[a]	42.4	22.2	14.2	98.7
Mean age (year)[b]	39.9	3.4	35.4	57.9
Disposable income per taxpayer (ISK thousands)[b]	5,485	647	4,230	7,382
Population[b]	7,065	19,898	43	131,136
Share of rural population (%)[b]	28.5	34.4	0	100
Size (km^2)[c]	1,511	2,273	2	12,021
Amount of municipal waste per capita (kg)[d]	507	286	116	1,297
Sum of recycling and recovery rate (%)[d]	45.6	33.1	0	100
2020				
Waste management cost per capita (ISK thousands)[a]	43.0	23.4	14.1	111.2
Mean age (year)[b]	40.1	3.6	35.2	59.2
Disposable income per taxpayer (ISK thousands)[b]	5,458	629	4,320	7,309
Population[b]	7,161	20,204	42	133,262
Share of rural population (%)[b]	28.4	33.5	0	100
Size (km^2)[c]	1,511	2,273	2	12,021
Amount of municipal waste per capita (kg)[d]	467	245	118	1,084
Sum of recycling and recovery rate (%)[d]	56.8	33.0	0.01	100
2021				
Waste management cost per capita (ISK thousands)[a]	43.4	25.2	11.5	127.9
Mean age (year)[b]	40.4	3.8	35.4	60.6
Disposable income per taxpayer (ISK thousands)[b]	5,894	1,146	4,384	10,760
Population[b]	7,306	20,573	42	135,688
Share of rural population (%)[b]	27.8	33.3	0	100
Size (km^2)[c]	1,511	2,273	2	12,021
Amount of municipal waste per capita (kg)[d]	525	296	134	1,665
Sum of recycling and recovery rate (%)[d]	58.4	32.0	0.01	100

Income and expenses are at 2022 prices; [a]Icelandic Association of Local Authorities (2023). [b]https://www.hagstofa.is/, [c]https://atlas.lmi.is/mapview/?application=markasja, [d]https://urgangur.is/maelabord/.

3.2. Methodology

Data Envelope Analysis (DEA) is a linear programming method used to evaluate the relative efficiency of decision-making units (DMUs) by benchmarking the performance of less efficient units against the fully efficient ones. DEA calculates an efficiency score for each DMU based on how efficiently they use their inputs to produce outputs, with a score of one indicating full efficiency and a score in the range]0,1[indicating inefficiency. The efficient units form an efficiency frontier, with the inefficient DMUs located below or above the frontier, depending on the approach taken.

In addition to identifying inefficient DMUs, DEA can also be employed to determine the sources of inefficiency. This information can then be used to improve performance and efficiency.

There are two central types of DEA models – input-oriented and output-oriented, which can be assumed to have a constant return to scale (CCR) (Charnes et al., 1978) or a variable return to scale (BCC) (Banker et al., 1984). The BCC model is used in this article because the municipalities are likely to operate at different scales. The input-oriented DEA model minimises the inputs needed to produce a given output and can, for instance, be used to determine how much costs (input) can be reduced while maintaining the same level of two outputs: solid waste per

Table 4
Pearson correlation matrix for the variables used in the regression analyses.

	Mean age	Disposable income	Population	Share of rural population	Size
Mean age	1				
Disposable income	−0.1493	1			
Population (log)	−0.5712***	0.3356***	1		
Share of rural population	0.4174***	−0.4126***	−0.6133***	1	
Size (log)	0.1903*	−0.4590***	−0.3894***	−0.5487***	1

The symbols ***and * indicate significance levels of 0.001 and 0.05 respectively.

capita, and recycling and recovery rates, as is done in this study The efficiency score shows the maximum proportion by which municipality (DMU's) inputs can be reduced without affecting the level of output. Such analysis identifies inefficient municipalities (DMUs) that use more inputs than necessary to produce their expected output.

Conversely, the output-oriented DEA model aims to maximise the outputs produced with a given quantity of inputs. The efficiency score in this model shows the maximum proportion by which municipality (DMU's) outputs can be increased without requiring additional inputs. In this article, an output-oriented DEA model calculates, for each municipality, the maximum amount of solid waste per capita, as well as the recycling and recovery rates (output) that could be handled while holding the current resources (input) fixed. As in the input-oriented model, the inefficient firms are benchmarked against the frontier formed by the efficient municipalities. Such analysis is useful for identifying DMUs that can produce more outputs relative to their inputs.

To gain deeper insights into the underlying factors that contribute to the efficiency scores from DEA, a second-stage DEA regression is commonly used to explore the relationship between the efficiency scores and various explanatory variables, thereby gaining insights into the determinants of efficiency among the DMUs in the dataset (Anang, 2022). This analysis often uses econometric techniques such as Generalized Least Squares (GLS). GLS is particularly useful in this context as it accounts for potential issues of heteroskedasticity and autocorrelation in the residuals, thus providing more efficient and unbiased estimates of the regression coefficients (Preinerstorfer and Pötscher, 2016).

3.3. Models used

Two different DEA models were employed to measure the waste management efficiency of Icelandic municipalities based on the available variables. Model I has one input variable (waste management cost per capita) and two output variables (the amount of municipal waste per capita reversed and the combined recycling and recovery rate). Model I is an input-oriented BCC model because the costs within municipalities are not fixed. It aims to evaluate municipal waste collection and expenditure efficiency performance and see how inefficient municipalities perform compared to efficient ones (Moraes e Soares, 2024). The model determines to what extent the cost of waste management can be reduced while maintaining the same level of waste per capita and rates of recovery and recycling. In Model I, the municipalities with the highest efficiency will have the lowest costs, the least waste, and the highest recycling and recovery rates. The second objective of Model I is to use the results for a second-stage analysis using Generalized Least Squares (GLS). In this analysis, the efficiency score will be the dependent variable, allowing us to explore its relationship with three socioeconomic variables and two geographic variables: mean age of inhabitants, disposable income per taxpayer, the logarithm of the population, the ratio of rural populations, and the logarithm of the municipality's size. Incorporating socioeconomic and geographic variables in the analysis can improve understanding of factors influencing efficiency (Molinos-Senante et al., 2023), and can yield important policy implications (Johnson and Kuosmanen, 2012), particularly in municipal waste management systems (Sarra et al., 2017), as socioeconomic and geographic characteristics are crucial in determining efficiency outcomes (Struk and Boďa, 2022).

Model II builds on Model I by adding the socioeconomic and geographic variables from the second-stage regression as input variables. Model II is an output-oriented BCC model since these variables are set within the municipalities and do not change or are hard to change. The second-stage DEA and Model II thus make it possible to compare how the socioeconomic and geographical variables impact efficiency from two directions: first, by examining whether they have a statistically significant effect on the efficiency scores from the regression analyses, and second, by analysing the characteristics of the municipalities based on the results from the output-oriented DEA. This comparison from two directions can highlight the robustness of certain variables across different modelling approaches, providing a clearer picture of their influence on efficiency outcomes. The models used in the analysis are summarised in Table 5.

This setup is similar to that found in Struk & Boďa (2022), who employed two input- and two output-oriented models with varying input and output variables in their analysis. Similarly, Ferraro et al. (2023) used two different input-oriented BCC models in their analyses, and Sarra et al. (2017) used input-oriented CCR and BCC models.

The calculations for the DEA models presented in this paper were

Table 5
Model configuration.

Model and interpretation		Input-output specification and orientation
Model I	**Inputs:**	Waste management cost per capita
The most efficient municipalities have the lowest costs, the least waste, and the highest recycling and recovery rates.	**Outputs:**	Waste per capita (reversed) Recycling and recovery rate
	Orientation:	Input
Model II	**Inputs:**	Waste management cost per capita
The most efficient municipalities have the least waste and the highest recycling and recovery rates relative to the input variable.		Mean age of inhabitants Disposable income per taxpayer (reversed) Population (logarithm, reversed) Ratio of rural populations Municipality's size
	Outputs:	Waste per capita (reversed) Recycling and recovery rate
	Orientation:	Output
Second stage DEA (GLS)	**Dependent variable:**	Efficiency scores from Model I
The regression explores the Relationship between efficiency and the input variable.	**Independent variables:**	Mean age of inhabitants Disposable income per taxpayer Population (logarithm) Ratio of rural populations Municipality's size

performed using the R programming language (R: The R Project for Statistical Computing, n.d.) with the assistance of the deaR (Coll-Serrano et al., 2023) and Benchmarking (Bogetoft and Otto, 2022) packages. For the calculations of second-stage regression analysis, VIF and correlation coefficients STATA 16.1 were used (StataCorp, 2023).

4. Results

A summary of the DEA analyses for the input-oriented Model I is presented in Table 6. It reveals that 7 out of 48 municipalities were fully cost-efficient in 2019, increasing to 9 in 2020, then returning to 7 in 2021, with three municipalities consistently efficient throughout the three years. Conversely, the number of municipalities with efficiency scores below 0.2 was 21 in 2019, 24 in 2020, and 13 in 2021, primarily due to high costs, waste levels, and low recycling rates. For example, the least efficient municipalities had waste management costs per capita that averaged over three times higher than those that were fully efficient, produced 37 % more waste per capita, and recycled and recovered 51 % less. The average efficiency scores were 0.40 in 2019, 0.38 in 2020, and 0.44 in 2021.

On a close look at the municipalities, the least efficient municipalities were larger but had smaller, less dense populations, with older residents and lower disposable incomes, while the most efficient municipalities showed greater diversity in geographical size and population. GLS regression was applied to the data to examine how the socioeconomic and geographic variables relate to the efficiency score. Table 7 shows the results from the regression analyses. The negative coefficient value for the mean age of inhabitants, disposable income and size indicates a negative relationship with efficiency and the positive sign for population and share of rural population. The relationship is statistically significant for the population, share of rural population and size but not for the mean age and disposable income.

In Model II, socioeconomic and geographic variables were added as input variables. Model II is output-oriented, focusing on how much the quantity of waste can be reduced and the rates of recovery and recycling increased while maintaining the same input level. The output-oriented Models II results are summarised in Table 8.

In Model II, results show that in 2019 and 2020, twenty-one out of forty-eight municipalities were fully efficient, dropping to twenty in 2021, with fourteen achieving full efficiency in all three years. The average efficiency scores were 0.88 in 2019, 0.85 in 2020, and 0.91 in 2021, with minimum scores of 0.22, 0.19, and 0.50, respectively. On a closer look at the municipalities, inefficient municipalities exhibited significantly higher per capita waste management costs, which were 125 % greater than those of their efficient counterparts. These municipalities had an approximately two years older population and 8 % lower disposable income. Notably, they accounted for only 9 % of the population within the efficient municipalities. Furthermore, inefficient municipalities were 115 % larger in terms of geographic size and had a 14 % higher proportion of rural residents. Among the forty-eight municipalities analysed, twenty-one consistently demonstrated inefficiency in Models I and II from 2019 to 2021, while five municipalities achieved efficiency only once, with most of these municipalities situated outside the capital area.

Table 6
Number of municipalities by efficiency score and descriptive statistics of efficiency scores of Model I.

Efficiency scores	2019	2020	2021
[0;0.2]	21	24	13
]0.2;0.4]	7	5	12
]0.4;0.6]	6	7	8
]0.6;0.8]	2	3	5
]0.8;1]	5	0	3
Of which fully efficient	7	9	7
Total	48	48	48
Minimum	0.01	0.01	0.02
Maximum	1.00	0.00	1.00
Mean	0.40	0.38	0.44
Standard Deviation	0.37	0.36	0.35

Table 7
Results of the regression analyses on the panel data.

Explanatory variable	GLS model Coefficient	(Standard Error)	*p*-value
Mean age	−0.01699	0.00974	0.081
Disposable income	−0.00001	0.00002	0.670
Population (log)	0.08985	0.03465	0.010*
Share of rural population	0.00475	0.00146	0.001**
Size (log)	−0.07949	0.01988	<0.001***
constant	1.29940	0.65874	0.021

The symbols ***, ** and * indicate significance levels of 0.001, 0.01 and 0.05 respectively

Table 8
Number of municipalities by efficiency score and descriptive statistics of efficiency scores of Model II.

Efficiency scores	2019	2020	2021
[0;0.2]	0	1	0
]0.2;0.4]	1	2	0
]0.4;0.6]	2	4	2
]0.6;0.8]	9	6	7
]0.8;1]	15	14	19
Of which fully efficient	21	21	20
Total	48	48	48
Minimum	0.22	0.19	0.50
Maximum	1.00	1.00	1.00
Mean	0.88	0.85	0.91
Standard deviation	0.18	0.22	0.14

The study enhances waste management efficiency by thoroughly analysing the factors that affect waste management practices in Icelandic municipalities. It addresses a gap in the literature concerning waste management efficiency in rural and Arctic areas, providing data-driven insights that can guide policy improvements. By examining the relationship between waste management costs, the amount of waste generated, and recycling rates, the study identifies municipalities that are operating inefficiently and uncovers the sources of that inefficiency.

5. Discussion

5.1. Overview of waste management efficiency

The DEA and GLS regression results provide an overview of waste management efficiency across 48 Icelandic municipalities in the years 2019–2021.

The regression analysis investigates the relationship between socioeconomic and geographic variables and efficiency, as outlined in Model 1, and the result aligns with the findings in Model 2. The regression results indicate that municipalities with larger populations tend to exhibit higher efficiency, while those with greater geographical areas are associated with lower efficiency.

When analysing municipalities identified as inefficient in Model 2, the data supports this trend; these municipalities generally have smaller populations and larger land areas. In contrast, efficient municipalities display a diverse range of geographical sizes and population densities, complicating the identification of an optimal municipal size for achieving efficiency. The regression analysis also reveals that the mean age of inhabitants and disposable income variables are not statistically significant with respect to the efficiency score. However, the negative coefficient for mean age suggests that less efficient municipalities tend to have older populations. Although disposable income does not appear

to influence efficiency in the regression, Model 2 indicates that inefficient municipalities typically have lower income levels compared to their efficient counterparts.

5.2. Population dynamics and their impacts

Moreover, the percentage of the rural population emerges as a significant factor in the regression analysis. One might anticipate a negative correlation for this variable, given that the municipalities classified as ineffective in Model 2 often have a higher proportion of rural residents, while more efficient municipalities tend to have denser populations. Notably, approximately 60 % of efficient municipalities have minimal or no rural population, whereas around 8 % consist entirely of rural residents. This finding highlights that while a dense population generally enhances efficiency, municipalities with small or negligible urban populations can still achieve efficiency. This complexity suggests that the relationship between efficiency and the proportion of the rural population is not straightforward.

Other studies indicate that the relationship between population density and efficiency is inconsistent, with some studies showing positive effects, others showing negative effects, and some showing no significance at all (Struk and Boďa, 2022). Struk and Boďa (2022) also argue that the optimal size of a municipality remains indeterminate and that per capita income plays a significant role in efficiency outcomes as it has been identified as a positive determinant of municipal solid waste management efficiency in various studies.

5.3. The role of collaboration and government support

It is important to highlight the influence that population size has on operational efficiency within municipal settings. Research suggests that municipalities at both ends of the population spectrum—namely, very small and very large communities—tend to demonstrate operational performance that frequently outstrips that of mid-sized municipalities (Sarra et al., 2017). This phenomenon can be attributed to several factors, including resource allocation, economies of scale, and the ability to implement specialised services. Smaller municipalities often enjoy streamlined decision-making processes and foster closer community engagement, while larger ones benefit from greater resource availability and the capacity for extensive infrastructure development. Consequently, the performance dynamic varies dramatically, with extremes in population size often leveraging their unique advantages to achieve superior operational outcomes compared to their mid-sized counterparts. Amaral et al. (2022) find that population size does not necessarily correlate positively with efficiency in waste management operations, as smaller populations often tend to have a more favourable operational environment. They can benefit from inter-municipal integration, which allows for sharing costs and resources and increases efficiency. Research indicates that joint service provision can achieve higher efficiency levels by increasing the size of the service, but this is most effective when the municipalities involved are adjacent and can collaborate effectively (Sarra et al., 2017).

Even though many municipalities in Iceland collaborate in waste management, the government could promote more collaboration between municipalities to increase efficiency. The best example of collaboration is Sorpa, a waste management company serving the capital area. Six municipalities in the capital area own it (Um SORPU, n.d.).

Additionally, the typology of municipalities—such as classifications of "rural"—has been illustrated to influence cost efficiency metrics (Rogge and De Jaeger, 2012). Previous studies (Sarra et al., 2017; Doussoulin and Colther, 2022) suggest that population density can both enhance and undermine efficiency, as the results of this study support, highlighting the necessity for further studies on the matter.

5.4. Legislative and structural challenges

The results highlight the significance of socioeconomic and geographic factors in waste management efficiency, which can guide policy and resource allocation (Molinos-Senante et al., 2023; Johnson and Kuosmanen, 2012). The two-stage DEA approach in this study improves understanding by including contextual variables like population socioeconomic and geography (Anang, 2022; Simar and Wilson, 2011).

Analysing municipalities that were never or only once efficient in the study reveals notable population trends over the last twenty years. Between 2001 and 2021, twenty of these municipalities experienced a decrease in population, averaging around 11 %. In contrast, the overall population of Iceland increased by 26 % during the same period. (Hagstofa Íslands, 2024). This trend adds a common factor among inefficient municipalities in Iceland. Municipalities experiencing depopulation have fewer resources to support the services they provide to residents, making it increasingly difficult for them to operate efficiently. The Icelandic government is aware of the depopulation of some municipalities and is currently supporting some of them through regional development projects (Icelandic Regional Development Institute, 2023). As previously mentioned, the depopulation challenges in Arctic regions, including Iceland and other remote rural areas globally, are becoming increasingly linked to the rising costs of waste management. These financial pressures are especially difficult for smaller municipalities, which often find it hard to develop sustainable solutions amid declining populations and limited resources. There are many similarities between Arctic municipalities and those in other regions (Burns et al., 2021; Sebastian and Louis, 2022; Liubarskaia et al., 2019; Nedoseka et al., 2021), as municipalities worldwide face comparable challenges in waste management, with smaller ones struggling to meet high legislative and governmental targets. In light of these challenges, authorities must consider governmental intervention, which may involve revised legislation or financial assistance, alongside the development of tailored and efficient waste management systems that account for population size, age distribution, income levels, and geographical constraints.

Socioeconomic and geographic factors are variables that local governments and policymakers cannot easily change, although municipal boundaries can be redrawn or merged according to government policy, potentially relying on economies of scale to enhance efficiency.

Inefficient municipalities use too many resources in their waste management system. These municipalities could enhance their appeal to residents by reallocating some of these resources. Options include improving desirable amenities, creating high-paying job opportunities, or offering lower taxes. This strategic shift could streamline waste management and contribute to overall community growth and efficiency. However, in the end, it all depends on the cost and benefits of resource reallocation and whether municipalities are able to reallocate.

Regarding the outputs used in the models, encouragement, policy, and legislation can influence the amount of waste generated. Public awareness campaigns can be implemented to reduce waste and promote recycling and recovery, specific harmful materials can be banned, and extended producer responsibility can also be enforced. Improvements to recycling infrastructure can be achieved by investing in sorting facilities and ensuring accessible drop-off centres to boost recycling rates. However, these investments are costly, and no government support is currently available for municipalities lacking the resources to invest. The lack of government support for municipalities lacking resources to invest in waste management infrastructure is a significant barrier to efficiency. This challenge corresponds closely with the findings of Moraes e Soares (2024), which emphasize the crucial role of efficient public expenditure in promoting sustainable waste management practices. Their research highlights that strategic allocation of financial resources not only optimizes waste management systems but also fosters long-term sustainability.

Legislation significantly influences the efficiency of waste

management in individual municipalities. Legislation is uniform across Iceland, with no assumed regional differences. Consequently, Iceland finds itself in a position similar to the Russian Arctic regions, where legislation does not fully consider the climatic and territorial specificities of individual regions (Nedoseka et al., 2021). This one-size-fits-all approach can hinder the development of tailored waste management strategies that address the unique environmental challenges faced by different areas. As a result, municipalities may struggle to implement effective waste management practices that align with local needs and conditions. Ultimately, the lack of regional adaptation in waste management legislation may compromise sustainability efforts and exacerbate environmental issues in various locales.

Another critical factor for waste management efficiency is adequate support from local authorities; Nedoseka et al. (2021) noted that the lack of support from authorities is the main obstacle to developing the recycling market. This situation is familiar to many Icelandic municipalities that require assistance to meet the waste management targets set by the government. Besides some financial aid to the most affected municipalities, there is the possibility of applying for exemptions from the law and regulations for isolated settlements and to postpone some deadlines for EU targets, as stipulated in the Amendments to Directive 1999/31/EC (European Commission, 2018a), as stated in Article 3(4), and the Landfilling Directive (EU, 2018/850) (European Commission, 2018b), Article 5(6). By postponing or granting exemptions from the law, the cost of waste management in the affected municipalities could be reduced, potentially leading to improved efficiency. However, this would compel the Icelandic government to abandon its ambitious waste management policy, as exemptions and postponements are not part of it.

The difficulties faced by Icelandic municipalities in waste management are not isolated; similar concerns are prevalent in other Arctic regions, as observed by Nedoseka et al. (2021) and Liubarskaia et al. (2019). While some municipalities achieved full efficiency, others struggled, particularly those in rural or remote areas. Understanding the various factors contributing to waste management inefficiencies across different Arctic settings can facilitate the identification of best practices and promote knowledge sharing among municipalities facing analogous challenges.

5.5. Limitations

Importantly, this study's DEA and the regression models have certain limitations. The efficiency scores are relative and depend on the municipalities included in the analysis. The results may also be influenced by the choice of input and output variables and the specific DEA model used. Additionally, the quality and availability of data can impact the accuracy and reliability of the results, as data from 21 municipalities are not included in this study; these 21 municipalities represent about 6 % of the Icelandic population and about 30 % of the size of Iceland, although over half of the municipalities included in the study share the same characteristics, the lack of data from these municipalities could potential biases the results. Improved data quality on municipal waste from all municipalities in Iceland would be desirable to achieve more robust results. Future research should consider a more extensive timeframe and include all Icelandic municipalities to provide a comprehensive understanding of waste management performance. Comparative studies across Arctic regions could also illustrate common challenges and potential solutions.

6. Conclusions

Even though the findings of this study are specific to Iceland, they align with other results, underlining the challenges of waste management in Arctic regions worldwide. The study highlights the significant challenges faced by municipalities in Iceland regarding waste management efficiency, particularly in the context of varying population sizes and geographic characteristics. The analysis reveals that densely populated municipalities tend to exhibit more efficient waste management practices due to better resource availability and infrastructure capacity. In contrast, smaller and remote municipalities struggle with inefficiencies, often exacerbated by increased demand and limited resources. The findings indicate that socioeconomic factors, such as disposable income and population demographics, affect waste management efficiency. Municipalities with higher disposable incomes and younger populations generally demonstrate better waste management outcomes.

Furthermore, the study identifies a pressing need for improved data quality and availability across all Icelandic municipalities, as the current lack of comprehensive data may bias results and hinder effective policymaking.

Based on these findings, we recommend a tailored approach for policymakers that considers the unique characteristics of each municipality. Policy suggestions include Investing in infrastructure improvements, particularly in smaller and remote municipalities, to enhance their waste management capacity, implementing community engagement initiatives to raise public awareness about waste reduction and recycling practices and providing financial assistance and exemptions from specific regulations for municipalities struggling with waste management efficiency to prevent widening disparities and encouraging the establishment of extended producer responsibility programs to hold manufacturers accountable for waste generated by their products.

By focusing on these targeted strategies, municipalities can enhance their waste management systems, ultimately leading to a more sustainable and healthier environment in the communities. Future research should explore the dynamics influencing waste management efficiency and include a broader range of municipalities to inform policy decisions effectively.

CRediT authorship contribution statement

Guðmundur Kristján Óskarsson: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sveinn Agnarsson:** Writing – review & editing, Supervision, Methodology. **Brynhildur Davíðsdóttir:** Writing – review & editing, Supervision.

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.

Data availability

All data are available at the given sources.

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Early determinants of packaging waste recovery under Iceland's 2023 EPR reform: Evidence from Grey Relational and econometric analysis

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ABSTRACT

This study examines the early effects of Iceland's 2023 extended producer responsibility (EPR) reform for packaging waste, one of the first nationwide implementations of a fully harmonised, producer-funded system in a small and geographically dispersed country. Using municipal-level data for 2023–2024, the analysis evaluates how socioeconomic, demographic, and infrastructural factors influence per capita collection of packaging paper and plastics. Grey Relational Analysis (GRA) is applied to identify the most influential determinants under limited data conditions, and pooled ordinary least squares (OLS) regression is used to estimate their statistical associations while controlling for region and year.

Results: show that paper recovery increased markedly in 2024, reflecting rapid adaptation to standardised collection, whereas plastic recovery remained largely unchanged. In this early two-year sample, municipal variation appears to be shaped primarily by structural and service-design factors rather than socioeconomic characteristics. A higher ratio of seasonal housing is associated with greater apparent per capita recovery, and a higher share of home collection is linked to lower recovery for both materials. The negative relationship between per capita costs and plastic recovery suggests diminishing returns to expenditure or reflects structural remoteness constraints that raise costs without increasing capture.

The findings highlight the importance of tailoring EPR implementation to the local context. Adjusting performance metrics for seasonal occupancy, optimising the curbside/drop-off collection mix, and refining fee distributions for structurally high-cost municipalities can improve equity and efficiency. Overall, EPR provides the financial and regulatory scaffold, but geography and system design ultimately determine realised recycling outcomes.

1. Introduction

Iceland is a high-income, sparsely populated Nordic island nation characterised by vast geographic distances, a population primarily clustered along the coastline, diverse settlement structures, and a strong dependence on resource-intensive industries. These factors pose distinctive challenges for environmental policy design and logistics (Mager et al., 2022; Óskarsson et al., 2022, 2025). With an average population density of approximately four persons per square kilometre, nearly two-thirds of the country's roughly 400,000 inhabitants reside in the Capital Region in the southwest, while the remainder are distributed across small and often remote municipalities, a distribution illustrated by the proportional circles in Fig. 1.

This demographic imbalance, combined with long transport distances and severe weather conditions, makes the provision of municipal waste management services particularly costly outside the capital area. As a member of the European Economic Area (EEA), Iceland is nevertheless required to implement EU waste and recycling targets, creating a structural tension between uniform policy obligations and highly uneven local operating conditions.

Extended producer responsibility (EPR) constitutes a central component of European waste policy, designed to transfer the financial responsibility for packaging waste management from municipalities to producers (Joltreau, 2022; Zehaie et al., 2024). In Iceland, the Icelandic Recycling Fund (Úrvinnslusjóður) implements this policy by collecting fees from producers and importers and distributing these funds to

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municipalities to cover most costs related to the collection and processing of packaging waste (Mager et al., 2022; Úrvinnslusjóður English, n.d.). Although the fund does not fully reimburse all municipal expenses, it provides an essential financial framework for national waste collection. The 2023 reform was not a response to a singular environmental crisis, but rather the culmination of long-term legislative efforts to align national waste management with the increasingly stringent recycling targets of the European Economic Area (EEA). This transition reflects a strategic shift from a system of 'fragmented' funding to a 'fully harmonised' national framework designed to provide the regulatory scaffold necessary for circularity. By internalising environmental costs into product prices, the policy aims to resolve the structural tension between uniform European obligations and the logistical realities of Iceland's sparse population and severe weather. Because Iceland's 2023 reform represents one of the first nationwide implementations of a fully harmonised, producer-funded packaging system in a small and dispersed country, it provides a rare real-world policy testbed for understanding how geography and system design shape early EPR outcomes. Prior to this reform, Iceland's packaging waste collection relied on a patchwork of fragmented, municipal-level arrangements that were only partially financed by producers, leading to significant variation in service accessibility and reporting. Without this legislative intervention, there is little basis for expecting a sustained nationwide increase or a highly uneven one, as smaller and more remote municipalities lacked the financial incentives and standardised infrastructure to independently scale up separate collection for materials with difficult handling profiles, such as plastics.

The legislative reform establishing the current EPR framework entered into force on 1 January 2023 through the Circular Law (Hringrásarlögin, 2023), which set specific mandates requiring municipalities to expand the separate collection of packaging waste, including plastic, paper, glass, and metal. Implementation, however, occurred in phases: while the financing framework applied nationwide from 2023, municipalities differed in the timing and speed with which collection systems were operationally adjusted, with some changes continuing into 2024. The empirical analysis, therefore, compares the first full year of operation under the new funding regime (2023) with the subsequent year (2024), capturing early adjustments rather than long-run equilibrium effects. The reform aimed to increase recycling rates and standardise waste management practices across Icelandic municipalities. Plastic and paper packaging are collected through multiple systems, such as household pickup, neighbourhood containers, and central collection facilities, whereas glass and metal are collected solely through drop-off systems. These differences in collection methods make plastic and paper packaging especially appropriate for evaluating municipal performance under the updated EPR framework. In Iceland, the financial mechanism of the Extended Producer Responsibility (EPR) scheme is administered by the Icelandic Recycling Fund (Úrvinnslusjóður), a statutory, publicly administered and independent fund established under national waste legislation (Hringrásarlögin, 2023; Lög um úrvinnslugjald, 2003). The Fund is not a Producer Responsibility Organisation (PRO) in the traditional sense, where producers or their agents directly manage and operate collection and recycling services, but instead functions solely as a financial administrator. Its primary role is to collect fees from producers and importers and redistribute these funds to municipalities to reimburse the costs associated with the separate collection and processing of packaging waste. Municipalities, therefore, remain the primary service providers, contracting collection and treatment services independently. Unlike many EU countries and other jurisdictions where operational Producer Responsibility Organisations manage both financing and logistics, Iceland's EPR system separates financial responsibility (centralised, state-administered) from operational responsibility (municipal service provision) (OECD, 2016). This separation is particularly consequential in small, rural, and remote municipalities, where operational constraints persist despite uniform national financing rules. The 2023 reform harmonised national collection requirements while maintaining this central funding structure, thereby providing a unified financial and regulatory scaffold for a small, geographically dispersed country.

International research indicates that socioeconomic variables, infrastructure types, and geographic context significantly influence recycling outcomes (Daoud et al., 2025; Gharagozloo and Ghazizade,

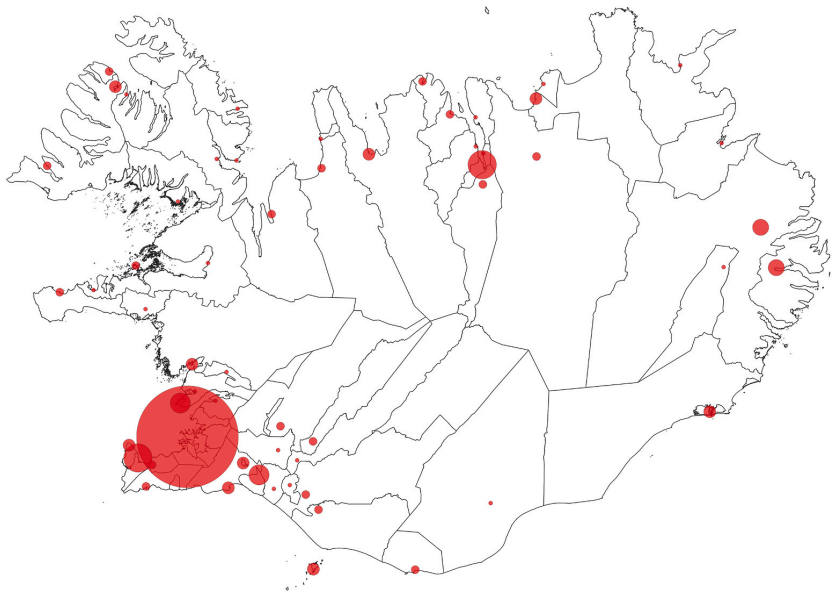


Fig. 1. Municipal structure and population distribution in Iceland. Municipal boundaries. The circles represent the relative population size of each municipality, illustrating the pronounced spatial concentration in the Capital Region in the south and the predominantly coastal settlement pattern across the country. (Sources: https://gatt.natt.is/, https://www.hagstofa.is/).

2023; Hondroyiannis et al., 2024). This spatial heterogeneity and the unique logistical constraints of Iceland's dispersed municipalities (Messmer, 2024; Óskarsson et al., 2022) highlight that the forces influencing recycling outcomes likely play out differently in this context. Previous work confirmed substantial variation in both cost structures and recycling performance across municipalities (Óskarsson et al., 2025). The 2023 EPR reform thus offers an opportunity to examine how local conditions modulate the effectiveness of producer-funded collection systems. The present study builds upon this foundation by focusing specifically on the determinants of packaging waste recovery under the new 2023 EPR framework.

This study analyses newly available municipal-level data on plastic and paper packaging collection for 2023 and 2024. Municipal performance is assessed using per capita collection rates, with a focus on socioeconomic, demographic, and infrastructural determinants. The analysis employs descriptive statistics, Grey Relational Analysis (GRA), and pooled ordinary least squares (OLS) regression to evaluate the importance of various factors and determine their statistical significance.

The following research questions guide the study:

1. How did per-capita collection of plastic and paper change between 2023 and 2024 following the EPR reform?
2. Which socioeconomic, demographic, and infrastructural factors are associated with variation in per-capita collection?
3. To what extent does the collection mix (home vs. drop-off/centres) shape outcomes, and do determinants differ between plastic and paper?

Addressing these research questions supports the evaluation of national policies and informs international discourse on EPR scheme design. The findings provide insights into how financial incentives, infrastructure choices, and local context interact to shape recycling outcomes in small, geographically diverse countries.

The analysis focuses on plastic and paper packaging, which are collected through household pickup, neighbourhood containers, and collection centres. This comprehensive approach allows for a detailed assessment of how collection methods influence performance. In contrast, glass and metal packaging are collected only through drop-off systems, limiting variation in collection modes and reducing their suitability for analysing municipal-level determinants of collection outcomes.

2. Literature review

The effectiveness of national packaging waste management depends on the financial and regulatory framework, collection infrastructure, and population behaviour, each shaped by local socioeconomic and geographic factors (Joltreau, 2022). This review examines literature in these areas, outlines the current state of knowledge, and identifies the research gap addressed by this study, which focuses on small, geographically diverse countries such as Iceland. Extended Producer Responsibility (EPR) is a central pillar of waste policy in Europe and globally, shifting the burden of waste management from public entities to producers and importers of goods (Campbell-Johnston et al., 2021; Diggle and Walker, 2022; Joltreau, 2022; Zhou and Luo, 2024). The primary objective of EPR is twofold: to internalise the environmental cost of packaging into product prices (financial responsibility) and to encourage eco-design through physical responsibility (Joltreau, 2022; Rodrigues et al., 2016). Despite these common principles, the concrete mechanisms for implementing EPR vary substantially across jurisdictions, reflecting differences in geography, institutional capacity, and settlement patterns.

EPR schemes typically rely on producer fees to finance waste collection, sorting, recycling, and recovery. However, the scope of these fees, the division of responsibilities, and the extent of producer involvement differ widely between systems. A critical distinction exists between so-called financial EPR models, in which producers fund municipal operations, and physical EPR models, in which producers also assume operational control over collection and treatment (Portugaise et al., 2023). While a well-designed EPR system can provide funding stability and enable comprehensive nationwide collection services, a recurring challenge across both models is that producer fees do not always cover the full range of waste management costs. Municipalities are therefore frequently left to absorb expenses related to public awareness campaigns, litter cleanup, and system adaptation (Gui et al., 2018; OECD, 2016; Rodrigues et al., 2016; Rubio et al., 2019).

Geography acts as a primary constraint on these implementation modalities, though administrative structures also play a critical role. The Adelphi study (Ahlers et al., 2021) demonstrates that differences in task allocation, legal definitions, and data quality significantly constrain one-to-one comparisons of EPR outcomes. Research from Canada further illustrates how financial EPR systems can weaken incentives for downstream recyclability when producers are detached from operational responsibility, instead favouring upstream cost reductions such as light-weighting (Portugaise et al., 2023). In geographically vast and sparsely populated regions, including northern and rural Canada, municipalities often retain logistical responsibility while relying on partial funding from Producer Responsibility Organisations, frequently through complex or voluntary contractual arrangements (Leclerc and Badami, 2024). These experiences underscore that harmonised EPR frameworks must be adapted to local geographic realities, particularly in remote or island contexts, and reinforce the observation that the absence of a globally aligned EPR strategy has produced a patchwork of national responses (Diggle and Walker, 2022).

To further clarify the determinants of recycling performance, the configuration of the collection system is critical, particularly the distinction between highly convenient curbside collection and voluntary drop-off systems. Convenience has consistently emerged as a key predictor of recycling participation, with curbside collection generally associated with higher recovery rates across demographic groups due to reduced time and effort for residents (Oluwadipe et al., 2022; Struk, 2017; Xirogiannopoulou et al., 2024). In the Icelandic context, the ongoing transition toward harmonised, separate collection provides a timely opportunity to examine how increasing system accessibility may influence overall recovery outcomes.

Recycling performance nevertheless varies widely across municipalities due to interacting infrastructural, socioeconomic, and contextual factors. At the infrastructural level, curbside systems tend to yield higher participation and capture rates, whereas systems requiring residents to transport recyclables to collection points often discourage engagement (Zhang et al., 2024). In Iceland, curbside collection is used primarily for paper and plastic packaging, while drop-off systems remain the sole mechanism for glass and metal recycling. Although less convenient, drop-off systems can be more cost-effective in low-density or remote areas and for heavier materials, often achieving lower contamination rates (Andersson and Stage, 2018; Dijkgraaf and Gradus, 2015; Ferronato et al., 2021). Similar patterns are observed internationally: in developing countries such as Nigeria and Benin, the physical presence of collection infrastructure is a stronger determinant of sustainable disposal behaviour than policy mandates alone, with the absence of facilities leading to widespread informal dumping regardless of regulatory intent (Xu, 2024a, 2024b). These findings suggest that across income levels, infrastructure availability constitutes a fundamental bottleneck for recycling performance.

Socioeconomic characteristics are also strong predictors of recycling behaviour. Higher income and education levels correlate positively with participation, reflecting both environmental awareness and access to resources (Abbott et al., 2011; Gharagozloo and Ghazizade, 2023). Housing type plays a similarly important role, with households in single-family dwellings generally outperforming those in multi-family or apartment buildings due to greater storage capacity and easier access to

collection (Du Toit and Wagner, 2020). In multi-family settings, convenience, management support, and accessibility are key determinants of participation (Ng, 2019), while meta-analytic evidence confirms that individuals in detached homes recycle more consistently than those in apartments or rented units (Geiger et al., 2019). Psychological and normative factors, including environmental concern, personal norms, and perceived social norms, further reinforce recycling engagement (Kotyza et al., 2024; Wilson et al., 2025; Zhang et al., 2024), particularly when supported by locally targeted, repeated, and motivational communication campaigns, which consistently outperform broad, generic outreach strategies (Liu et al., 2022; Oluwadipe et al., 2025; Trushna et al., 2024).

Geographic and contextual conditions further compound these dynamics. Lower population density and longer collection distances increase per-unit costs and reduce efficiency, while municipalities with substantial seasonal housing or tourism experience pronounced fluctuations in waste volumes that distort per capita metrics and strain static infrastructure (Arbulú et al., 2024; Molinos-Senante et al., 2022; Söderberg et al., 2025). In the Icelandic context, these challenges are further intensified by severe weather conditions and extreme geographic isolation. Seasonality remains a persistent blind spot in standard EPR evaluations. In tourism-intensive regions such as Tuscany, coastal Cyprus, and the Algarve region of Portugal, seasonal population surges undermine operational efficiency and necessitate specialised indicators to handle peak demand (Caponi, 2022; Mendes et al., 2013; Voukkali et al., 2023). Iceland's current reliance on a dual-model, utilising curbside collection for paper and plastic while maintaining drop-off points for glass and metal, offers a unique opportunity to evaluate how these differing collection infrastructures perform under such distinct Arctic constraints. These dynamics are increasingly exacerbated by global consumption trends, including the expansion of fast fashion and textile waste streams, which further burden municipal systems struggling to divert material from landfills (Juanga-Labayen et al., 2022).

Although Iceland is a high-income country, its waste management system faces pressures analogous to those observed in both rural regions of the Global North and rapidly urbanising areas of the Global South. Empirical studies from rapidly growing cities such as Gujranwala, Pakistan, and Visakhapatnam, India, show that rising waste volumes associated with urban expansion can quickly overwhelm existing collection and treatment capacity, requiring differentiated strategies across income groups and seasonal demand patterns (Ali et al., 2019; Cheela et al., 2021). Research shows that urbanisation and economic expansion are systematically associated with higher solid waste generation (Chen, 2018), creating a 'double-edged sword' in which development intensifies environmental pressures on local authorities (Voukkali et al., 2023). In Iceland, seasonal tourism and internal population concentration generate a form of micro-urbanisation that places disproportionate stress on municipal systems, particularly in small and remote communities.

Despite extensive international research on recycling determinants, few studies examine how infrastructural constraints, socioeconomic drivers, urbanisation-like pressures, and seasonality interact jointly under a producer-funded EPR framework in small, geographically dispersed nations. Arctic and island contexts remain especially underrepresented. The Icelandic case, therefore, offers valuable insight into how demographic, infrastructural, and geographic conditions shape recycling performance under a harmonised national policy. Building on this gap, the present study leverages the natural experiment created by Iceland's 2023 EPR reform, which introduced mandatory, harmonised separate collection while maintaining producer funding.

3. Data

The analysis, which covers 2023 and 2024, is based on municipal-level data from multiple official Icelandic sources, corresponding to the first two years of Iceland's reformed extended producer responsibility (EPR) scheme for packaging waste. The central dataset comes from the Icelandic Recycling Fund.

The Recycling Fund dataset provides detailed information on the quantity of packaging waste collected by material type and by collection channel. Packaging materials are collected through three distinct methods: household collection (home pickup), neighbourhood container collection, and central collection centres. This study focuses on plastic and paper packaging because they are collected through all three channels, allowing for variation in collection methods across municipalities. Heavier packaging streams, such as glass and metal, were excluded from the analysis due to a lack of variation in collection modes. All other household and commercial waste streams are excluded; only packaging materials collected under the EPR system are analysed.

To account for local demographic, economic, and infrastructural conditions, additional variables were obtained from various national databases. Demographic and socioeconomic indicators (population size, mean age, and mean income) were sourced from Statistics Iceland, while per capita waste management costs came from the Association of Icelandic Municipalities. Housing structure and seasonal housing data (number of single-family houses, apartments and cottages) were obtained from the National Property Registry, and municipal area size was derived from the Icelandic Spatial Data Infrastructure. The cottage ratio variable was calculated as the number of registered cottages divided by the total number of permanent dwellings. Because several municipalities have extensive tourism or second-home areas with few permanent residents, the ratio can exceed 1, and in some extreme cases, cottages outnumber dwellings by more than a factor of ten. All monetary values are expressed in Icelandic krónur (ISK) in 2024 prices. For reference, 150 ISK is approximately equal to 1 euro based on average exchange rates in 2024.

The dependent variables are the per capita collection rates for plastic and paper packaging (kg/person) under the national EPR system. Explanatory variables include the share of single-family houses, the share of collection conducted at home, the log of population size, the ratio of cottages to total housing, the return payment per kilogram received from the Recycling Fund, and the per capita waste management cost. The dataset covers all Icelandic municipalities, with the capital region aggregated into a single observation for comparability. After excluding ten municipalities with incomplete or missing data, the final analytical sample consists of 49 municipal units (48 individual municipalities plus the aggregated capital region) observed over two years (2023–2024), yielding 98 observations in total.

4. Methodology

To address the data constraints inherent in small-scale municipal systems, the study employs complementary analytical techniques. Grey Relational Analysis (GRA) is used for its flexibility in modelling systems characterised by limited, incomplete, or interdependent data (Gerus-Gościewska and Gościewski, 2022; Nayakappa et al., 2019). GRA enables the assessment of the relative influence, or grey relational grade, of key variables such as collection method share, population density, and seasonal housing on per capita recovery, and has been successfully applied in municipal solid waste and environmental management contexts under conditions of uncertainty (Luo et al., 2021). In addition, the analysis of a two-year municipal panel (2023–2024) draws on pooled Ordinary Least Squares (OLS) regression with robust standard errors and fixed effects at the year and regional level. Although the panel is short, pooled OLS represents a parsimonious and widely adopted approach in environmental and municipal studies when data availability is constrained (e.g. Nan et al., 2023).

The analytical framework combines descriptive, exploratory, and inferential techniques to examine the initial performance of Iceland's reformed extended producer responsibility (EPR) system for packaging waste. The analysis focuses on the first two years of the reform (2023–2024), capturing municipal-level variation in per capita

collection of plastic and paper packaging, collection methods, and key socioeconomic and infrastructural characteristics.

The study proceeds in three stages. First, descriptive statistics summarise the distribution and variation of key indicators across municipalities, providing an overview of early implementation outcomes. Second, Grey Relational Analysis (GRA) (Deng, 1989) is employed to assess the relative strength of association between per capita collection rates (for plastic and paper) and a set of explanatory factors, including housing structure, collection method, population size, seasonal housing ratio, return payment per kilogram, and waste management cost per capita. GRA was selected for its suitability in small-sample contexts with interdependent or heterogeneous data (Fan and Fan, 2019; Javanmardi et al., 2020; Wang et al., 2018; Yang et al., 2022).

In GRA, variables are first normalised to ensure comparability. The grey relational coefficient between a reference sequence x_0 (e.g., plastic per capita) and each comparison sequence x_i is computed as:

$$\xi_i(k) = \frac{\min_i \min_k \left|x_0(k) - x_i(k)\right| + \rho \max_i \max_k \left|x_0(k) - x_i(k)\right|}{\left|x_0(k) - x_i(k)\right| + \rho \max_i \max_k \left|x_0(k) - x_i(k)\right|} \quad (1)$$

Where $\xi_i(k)$ is the coefficient for variable i at indicator k, and ρ is the distinguishing coefficient, conventionally set to 0.5 (Javanmardi et al., 2020). The Grey Relational Grade (GRG) for each variable is obtained by averaging $\xi_i(k)$ across all k, yielding a dimensionless score between 0 and 1 that expresses the strength of association between the variable and the reference series.

Finally, pooled Ordinary Least Squares (OLS) regression models are estimated to identify statistically significant determinants of per capita collection (Ella et al., 2022; Przydatek and Ciągło, 2020). Separate models are specified for plastic and paper using the short municipal panel (2023–2024), which allows both cross-sectional and short-run variation while retaining time-invariant covariates. The general model can be expressed as:

$$Y_{it} = \alpha + \beta_1 X_{1,it} + \beta_2 X_{2,it} + \cdots + \beta_k X_{k,it} + \mu_r + \lambda_t + \varepsilon_{it} \quad (2)$$

Where Y_{it} is the per capita collection of packaging waste (plastic or paper) in municipality i and year t; X_k are explanatory variables (single-family housing ratio, collection-at-home share, log population, cottage ratio, return payment per kilo, and waste management cost per capita); μ_r and λ_t represents region and year effects; and ε_{it} is the error term. Regional dummy variables were included to control for broad geographic effects (eight statistical regions, with the capital region as the reference category).

The models are estimated using cluster-robust standard errors to ensure valid inference under potential non-constant variance and cross-municipal heterogeneity (Colin Cameron and Miller, 2015; Stock and Watson, 2008).

For a very short panel (T = 2), a fixed-effects (FE) specification would absorb nearly all cross-sectional variation and significantly reduce degrees of freedom (Schmidheiny, 2024). In such short panels, pooled regression with region and year controls provides a pragmatic alternative that captures broad contextual effects while retaining between-municipality variation (Wooldridge, 2025). The random-effects model requires an assumption that municipal traits and error terms are uncorrelated, which is unlikely to hold in this context. This makes pooled OLS with robust inference a practical and widely used choice (Wooldridge, 2002).

Diagnostics and robustness checks, including alternative FE/RE specifications and clustered/robust errors, were conducted in line with standard panel-data practice (Colin Cameron and Miller, 2015; Wooldridge, 2025). Preliminary models also included mean income as a control variable; however, it was excluded from the final specification as it was not statistically significant and did not improve model fit. Together, these complementary methods provide both an exploratory and confirmatory understanding of how municipal characteristics and collection system design influenced the early outcomes of Iceland's new EPR scheme for packaging waste.

The pooled ordinary least squares (OLS) models were estimated using the R programming language (R: The R Project) to analyse panel data. The plm package (Croissant and Millo, 2008) was used for model estimation, while the lmtest (Zeileis and Hothorn, 2002), sandwich (Zeileis, 2004), and clubSandwich (Pustejovsky, 2016) packages were employed to compute robust standard errors. The Grey Relational Analysis was performed using Microsoft Excel.

5. Results

Descriptive statistics for 2023 and 2024 are presented in Table 1, providing an overview of early outcomes under Iceland's reformed extended producer responsibility (EPR) system. The analysis focuses exclusively on plastic and paper packaging waste collected under the national EPR framework, excluding other recyclable materials such as glass or metals. Across 49 municipalities, per capita plastic collection averaged 10.3 kg in 2023 and 10.2 kg in 2024, while paper collection increased from 28.6 kg to 34.0 kg per capita. The expansion of household collection services is evident in the rising share of plastic collected at home, from 66 % to 73 %, although the paper home-collection ratio remained stable. Both plastic and paper return payments per kilogram increased between the two years, particularly for plastics, reflecting the progressive rollout of the EPR fee system. Mean waste-management costs per capita were relatively stable but highly variable across municipalities, with standard deviations exceeding 40,000 ISK, consistent with large spatial differences in service organisation and transport costs.

Municipal demographic indicators also showed substantial heterogeneity. Populations ranged from fewer than 100 inhabitants in the smallest rural municipalities to over 200,000 in the capital region. When included, the capital region substantially raises the standard deviation of population (mean ≈ 6400; SD ≈ 31,000), reflecting Iceland's highly uneven settlement distribution. Housing structures were dominated by single-family dwellings (average ≈ 79 %), and seasonal housing ratios varied widely, indicating the continued influence of tourism and second-home ownership on local waste flows. In some municipalities, the number of cottages greatly exceeds the number of permanent dwellings, resulting in cottage ratios above 1. This reflects the high prevalence of second-home and tourism properties in certain rural or coastal areas. These contextual differences underline the relevance of examining how socioeconomic and infrastructural variables jointly shape collection outcomes.

Grey Relational Analysis (GRA) assessed the relative importance of candidate determinants for per capita plastic and paper collection

Table 1
Descriptive statistics at the municipal level (2023–2024).

Variable	2023 Mean	2023 SD	2024 Mean	2024 SD
Plastic per capita (kg/person)	10.3	7.1	10.2	8.5
Paper per capita (kg/person)	28.6	18.8	34.0	27.0
Plastic home collected ratio (share of total plastic collection)	0.66	0.32	0.73	0.28
Paper home collected ratio (share of total paper collection)	0.58	0.30	0.56	0.30
Population	6360	31,062	6504	31,702
Cottage ratio (cottages/total dwellings)	0.94	2.70	0.92	2.62
Single-family housing ratio (share of dwellings)	0.79	0.16	0.79	0.17
Plastic return payment per kilo (ISK/kg)	153	65	214	112
Paper return payment per kilo (ISK/kg)	90	37	90	50
Waste cost per capita (ISK/person)	70,383	43,783	70,679	58,766

(Deng, 1989; Fan and Fan, 2019). The reference sequences were plastic per capita and paper per capita, respectively. Comparative sequences included the share of single-family houses, cottage ratio, logarithm of population, share of collection conducted at home, return payment per kilogram, and waste-management cost per capita. All variables were normalised using the larger-the-better criterion, except waste cost, where the smaller-the-better criterion was applied. The Deng (1989) method was adopted with a distinguishing coefficient $\rho = 0.5$ and global min-max. As reported in Table 2, for both materials, the cottage ratio exhibited the strongest Grey Relational Grade (0.81 for plastic; 0.83 for paper), indicating a strong association between the prevalence of seasonal housing and per-capita recovery. While GRA does not reveal directionality, subsequent regression analysis (Section 5) shows that this relationship is positive, meaning municipalities with more seasonal housing record higher apparent per-capita collection, partly because population denominators do not capture temporary occupancy. This pattern partly reflects inflated per capita figures in municipalities with substantial seasonal or tourist housing, where the registered population (used as the denominator) does not fully capture temporary occupancy. Return payment per kilogram and log population also showed relatively high GRGs (≈0.70), suggesting that financial incentives and scale effects matter. In contrast, the collection-at-home share and single-family housing ratio had moderate relational grades (≈0.50), and waste-management cost per capita was least related to recovery performance. Overall, the GRA results imply that structural and financial factors exert greater influence on collection outcomes than housing composition alone.

To further investigate the relationships between various factors and per capita collection rates, we used pooled Ordinary Least Squares (OLS) regression models (Colin Cameron and Miller, 2015; Wooldridge, 2002), incorporating region and year effects. The application of cluster-robust standard errors allowed us to address cross-municipal variance effectively. The findings of these analyses are encapsulated in Table 3.

The regression analysis reveals a strong negative association between the share of home collection and per capita plastic recovery ($p < 0.001$), with municipalities relying more heavily on household systems collecting substantially less plastic per resident. Seasonal housing intensity is positively associated with plastic recovery ($p < 0.01$), while higher waste-management costs are not associated with higher recovery, suggesting diminishing returns to expenditure. A similar pattern is observed for paper packaging. The share of home collection is again negatively associated with recovery ($p < 0.001$), whereas seasonal housing intensity remains a significant positive predictor ($p < 0.05$). In addition, paper recovery is significantly higher in 2024 than in 2023, indicating an early improvement for paper following the reform. Taken together, the results indicate that seasonal population fluctuations and collection-system design are the primary drivers of recovery performance. Increasing convenience through home collection alone does not guarantee higher yields, and early EPR outcomes in Iceland appear to be shaped more by spatial and structural factors than by socioeconomic characteristics or expenditure levels.

6. Discussion

The observed surge in paper recovery in 2024, contrasted with the stability of plastic collection, underscores the uneven impact of shifting from the pre-2023 ‘patchwork’ system to a harmonised framework. While the legislative reform provided the necessary financial scaffold, the results suggest that paper, a material with a more established collection history in the Nordic context, adapted more rapidly to the new national standards. In contrast, the lack of immediate improvement in plastic recovery suggests that the ‘structural tension’ identified in the Introduction remains a binding constraint; uniform funding alone cannot immediately overcome the logistical barriers and contamination risks inherent in Iceland's remote municipalities. The results provide an early assessment of Iceland's harmonised EPR reform for packaging waste and speak directly to the policy goals outlined in the Introduction. In line with the reform's intent to standardise separate collection and stabilise funding via producer fees (Hringrásarlögin, 2023; Joltreau, 2022; OECD, 2016), paper recovery rose between 2023 and 2024, suggesting rapid behavioural and operational adaptation as systems matured and fee schedules propagated through local provision. That plastic recovery remained largely flat indicates that harmonisation and producer funding are necessary but not sufficient for materials with different handling and contamination profiles, an outcome consistent with the broader EPR literature showing that scheme design and on-the-ground implementation details mediate performance (Ahlers et al., 2021; Campbell-Johnston et al., 2021; Rubio et al., 2019). This pattern is also consistent with the distinction between financial and physical EPR models: when producers primarily fund municipal operations rather than managing recovery directly, outcomes depend heavily on local service design, logistics, and operational capacity rather than on producer-side optimisation alone (OECD, 2016; Portugaise et al., 2023). In such financial EPR settings, upstream cost-saving incentives (e.g., lightweighting) may not translate into improved downstream capture unless collection and sorting systems are concurrently adapted (Portugaise et al., 2023).

Two structural determinants stood out across GRA and pooled OLS: the cottage ratio and the share of home collection. Municipalities with higher seasonal housing exhibited higher per capita recovery for both materials. As documented in tourism-intensive regions like Tuscany and the Algarve, seasonal surges create a mismatch between the registered population and the actual waste-generating population (Caponi, 2022; Mendes et al., 2013). In Iceland, this manifests as a positive correlation between cottage ratios and recovery, which should be viewed primarily as a statistical inflation caused by unregistered temporary inhabitants rather than a sign of increased recycling efficiency. This pattern is likely due to denominator bias from unregistered temporary populations (Arbulú et al., 2024), where waste management costs and volumes are significantly influenced by a municipality's actual service population rather than just its registered residents. Furthermore, short-term visitors are often less familiar with local sorting rules, which can lead to higher contamination rates in municipalities with high seasonal occupancy (Mendes et al., 2013). This suggests that while these municipalities show higher ‘apparent’ per capita recovery, the realised recycling quality may actually be lower than in stable resident populations. Per capita indicators should be interpreted cautiously because waste management costs are significantly influenced by a municipality's population size and density. For example, studies show that smaller municipalities can achieve notable cost savings through collaborations with larger neighbours (Molinos-Senante et al., 2022; Söderberg et al., 2025). For benchmarking and funding allocation within EPR, these findings suggest supplementing standard per capita metrics with service-population measures or per-household/per-service-point indicators to avoid over- or under-stating performance in municipalities with pronounced seasonal flux. Similar implementation challenges have been documented in geographically dispersed parts of Canada, where municipalities remain operationally responsible, and performance is shaped by high transport costs and limited economies of density, reinforcing the need for context-adjusted metrics and funding rules in remote jurisdictions (Leclerc and Badami, 2024).

Table 2
Grey Relational Analysis (GRA) between the collection of plastic and paper per capita and potential.

	Plastic per capita	Paper per capita
Cottage ratio	0.806	0.834
Return payment per kilo	0.708	0.704
Log population	0.692	0.670
Collection at home share	0.505	0.544
Single-family housing ratio	0.501	0.492
Waste mgmt. cost per capita	0.430	0.423

Table 3
Result of a Pooled Ordinary Least Squares (OLS) robust regression on plastic per capita and paper per capita.

Variable	Plastic Coef.	Plastic SE	Plastic Sig.	Paper Coef.	Paper SE	Paper Sig.
Intercept	12.747	7.501	0.093	9.732	41.416	0.815
Single-family housing ratio	8.537	4.727	0.074	28.769	25.113	0.255
Collection at home share	−11.407	3.196	<0.001	−31.233	8.693	<0.001
Log population	0.190	0.563	0.736	2.25	2.846	0.431
Cottage ratio	2.127	0.753	0.006	5.103	1.990	0.012
Return payment per kilo	0.00011	0.005	0.982	−0.032	0.0398	0.424
Waste mgmt. cost per capita	−4.6e-05	1.7e-05	0.011	−3.7e-05	5.9e-05	0.532
Region dummies	included	–		included	–	
Year 2024	0.809	0.754	0.286	6.173	2.393	0.011
Observations	98	–		98	–	
R^2	0.706	–		0.614	–	
Adj. R^2	0.656	–		0.549	–	
F-statistic	14.22	$p < 0.001$		9.44	$p < 0.001$	

Notes: Dependent variables are the per capita collection of plastic and paper packaging waste under the national EPR system. Region dummy variables (7 regional indicators; capital region as reference, not shown) and a year dummy (2024) were included in all models. Cluster robust standard errors are reported.

While contamination and tourist participation were not directly observed in this study, this mechanism offers a plausible complementary explanation for the strong association between seasonal housing intensity and per-capita collection outcomes. Notably, the positive relationship between seasonal housing and recovery likely reflects a denominator bias, where waste from unregistered visitors is attributed to the small permanent population.

By contrast, the home-collection share showed a consistent negative association with recovery performance. Although curbside service is commonly assumed to enhance recycling through convenience, this effect depends on design parameters. In Iceland's low-density municipalities, the negative coefficient for home collection suggests that operational capacity constraints override the convenience effect. Because household systems typically rely on smaller bins and lower pickup frequency to control costs, they mechanically limit set-out volumes. Drop-off sites, on the other hand, can accommodate larger loads with better compaction and contamination control, resulting in higher net captured tonnage per resident.

Therefore, the lower recovery in high-service areas should not be interpreted as evidence that home collection reduces recycling intent, but rather that the physical infrastructure in these regions is currently a binding constraint on total capture.

Comparable findings have been documented in other European and Nordic settings, where container size, pickup frequency, and contamination management at drop-off stations have been shown to mediate the relationship between convenience and recycling performance (Andersson and Stage, 2018; Dijkgraaf and Gradus, 2015; Struk, 2017; Xirogiannopoulou et al., 2024). Although container volumes and pickup frequencies were not observed in this study, these mechanisms provide a plausible interpretation of the negative coefficient and are consistent with the international evidence on how service design shapes recycling outcomes.

The weak role of classic socioeconomic covariates in our short panel, relative to structural/infrastructural variables, is also instructive. This emphasis on infrastructure and system capacity over socioeconomic gradients aligns with evidence from rapidly urbanising settings, where rising waste volumes and limited service provision can overwhelm behavioural differences and make the physical availability and organisation of collection the binding constraint (Ali et al., 2019; Cheela et al., 2021; Xu, 2024a, 2024b). Income, education, and housing type are frequently studied socioeconomic factors that have been shown to influence recycling behaviour in many contexts (Abbott et al., 2011; Du Toit and Wagner, 2020; Geiger et al., 2019; Ng, 2019). Iceland's small, dispersed municipalities face strong logistical constraints and seasonal demand shocks that can dominate behavioural gradients. The negative association between waste-management cost per capita and plastic recovery further suggests diminishing returns to expenditure in low-density and remote areas, where marginal spending is absorbed by distance and weather rather than by service enhancements that raise net capture, an interpretation aligned with documented cost heterogeneity in Iceland and the Nordics (Ahlers et al., 2021; Óskarsson et al., 2022; Söderberg et al., 2025). Within an EPR framework, this argues for targeted adjustments (e.g., remoteness or ferry-leg modifiers) to producer-fee disbursements so that structurally high-cost municipalities are not penalised for geography, while still maintaining the core EPR principle that producers finance end-of-life management (Gui et al., 2018; OECD, 2016).

Methodologically, the joint use of GRA and pooled OLS proved valuable for small-sample municipal analysis. GRA prioritised determinants under data constraints typical of early reform years (Deng, 1989; Fan and Fan, 2019; Javanmardi et al., 2020; Yang et al., 2022), while regression with robust inference quantified their conditional effects on region and time (Colin Cameron and Miller, 2015; Stock and Watson, 2008; Wooldridge, 2002). That both approaches singled out seasonal housing and collection mix strengthens confidence in these conclusions and complements prior Iceland-specific diagnostics of plastics value-chain potential and municipal heterogeneity (Mager et al., 2022; Óskarsson et al., 2022). At the same time, we emphasise that these are initial, two-year results; as the reform matures and operations stabilise, the balance of effects may shift, particularly if municipalities enhance collection capacity through changes in container size, pickup frequency, and tightened contamination controls in household systems, interventions suggested by the literature and consistent with our coefficient magnitudes (Andersson and Stage, 2018; Struk, 2017; Xirogiannopoulou et al., 2024).

This study also builds directly on earlier research evaluating municipal waste management efficiency in Iceland using Data Envelopment Analysis (Óskarsson et al., 2025). Whereas that analysis quantified the relative efficiency of municipalities based on cost, recycling, and demographic characteristics, the present paper extends the investigation by identifying the determinants of performance under the new producer-funded system. Together, the two studies provide complementary perspectives on Icelandic waste management: the DEA framework assessed how efficiently municipalities transformed resources into recycling outcomes before the 2023 reform, while the current analysis examines how structural, demographic, and system-design factors shaped recovery during the early years of the EPR regime. Viewed jointly, they offer a more comprehensive understanding of how financial mechanisms and local context interact to determine recycling performance in small and geographically diverse systems. The following section outlines specific implications for EPR policy design and implementation in Iceland.

6.1. Policy implications

The findings from this early assessment of Iceland's new Extended

Producer Responsibility (EPR) scheme suggest several critical adjustments for policy and implementation to enhance equity and efficiency across geographically diverse municipalities.

First, performance indicators must explicitly account for seasonal occupancy and tourism load, not just the registered population (Ahlers et al., 2021; Arbulú et al., 2024). Reliance on registered population figures as the sole denominator risks overstating performance in tourism-intensive municipalities and can lead to unfair benchmarking and inequitable allocation of producer-funded reimbursements.

Second, collection system design matters as much as funding: the negative association with home collection suggests that curbside service should be adapted to local density and geography, balancing convenience with container size, pickup frequency, and contamination control. Hybrid systems that combine household and well-managed bring points may yield better overall recovery, particularly for materials like paper (Dijkgraaf and Gradus, 2015; Struk, 2017; Xirogiannopoulou et al., 2024).

Third, EPR fund distribution formulas could incorporate structural modifiers, for instance, accounting for remoteness or transport distance, to prevent geographically disadvantaged municipalities from being penalised for unavoidable logistical costs (OECD, 2016; Rodrigues et al., 2016; Rubio et al., 2019).

By demonstrating how geography and system configuration mediate recycling outcomes even under uniform regulation, the Icelandic case offers valuable lessons for other small or geographically dispersed jurisdictions pursuing circular economy targets under similar EPR schemes.

6.2. Limitations

These limitations qualify the conclusions of the study but also point to a clear agenda for future research. First, the analysis is constrained by the availability of harmonised municipal-level data, which commenced with the implementation of the reformed EPR framework on 1 January 2023. Comparable data prior to this date are unavailable, as the standardised reporting categories required for the analysis were established by the reform itself. Consequently, it is not possible to test for pre-existing trends or to employ difference-in-differences designs that would more definitively isolate policy effects from potential confounding factors. The observed increase in paper recovery in 2024 should therefore be interpreted as a short-run change coinciding with the early implementation period, rather than as a causal effect confirmed against a longer historical baseline.

Second, the panel spans only the first two years of the new regime (2023–2024). As a result, the findings reflect short-run adaptation and adjustment rather than long-run equilibrium outcomes of the EPR system. Extending the time horizon will improve statistical precision and permit the use of stronger causal research designs as municipalities and producers fully adapt to the harmonised framework.

Third, several potentially important mechanisms could not be observed directly. The analysis relies on per capita recovery measures based on registered population and does not incorporate service-population denominators or direct indicators of tourism load, such as guest-nights or mobility-based measures. Nor does it include information on contamination rates, set-out behaviour, or participation intensity. While the cottage ratio and related proxies partially capture seasonal population dynamics, future work incorporating richer operational and behavioural data would allow more precise identification of the mechanisms underlying observed associations (Arbulú et al., 2024; Wilson et al., 2025).

Fourth, institutional and operational heterogeneity across municipalities may influence outcomes in ways not fully captured by the available variables. Differences in container capacity, collection frequency, contractor arrangements, and local communication strategies could affect recovery performance, but are not observed in the dataset. These unmeasured factors may help explain residual variation in municipal outcomes.

Finally, material scope also constrains interpretation. Glass and metal packaging are currently collected exclusively through drop-off systems, limiting variation across collection modes for these streams. As collection practices evolve and greater variation emerges, future research could expand the material scope to enable a more comprehensive comparison of how different packaging streams perform under the EPR architecture.

Overall, the findings should be interpreted as early, short-run associations observed during the initial phase of implementation, rather than as definitive estimates of long-run causal effects. Despite these limitations, the analysis provides a valuable first assessment of how geography, seasonality, and system design shape early EPR outcomes in a small, geographically dispersed country. Future research exploiting longer post-reform panels will be necessary to assess whether these early patterns persist.

7. Conclusion

This study provides an early, two-year assessment of Iceland's harmonised EPR regime for packaging paper and plastics using municipal data for 2023–2024, combining Grey Relational Analysis with pooled OLS to identify and test the main drivers of collection outcomes. Regarding overall effects (RQ1), paper recovery increased meaningfully from 2023 to 2024 while plastic recovery remained broadly unchanged, coinciding with the early implementation of the reform and suggesting short-run performance gains for paper but that plastics face material-specific constraints in the short run. As to the determinants of municipal variation (RQ2), outcomes were shaped far more by structural and infrastructural conditions than by classic socioeconomic characteristics: municipalities with higher seasonal-housing intensity collected more per person, and systems with a greater share of home collection collected less per person, with per capita costs showing diminishing returns for plastics. On the role of collection methods and material differences (RQ3), the negative association between home-collection share and recovery for both materials is a pivotal finding, suggesting that the effectiveness of convenience is highly mediated by system design, container capacity, and contamination control in low-density areas. While the broad determinants are similar across materials, paper saw a significant performance gain in 2024, whereas plastic recovery remained constrained by short-run factors. The core conclusion is that EPR appears to provide the necessary funding scaffold, but geography, seasonal population fluctuations, and the operational details of the collection system ultimately determine realised recycling outcomes in small, dispersed jurisdictions. The results underscore the critical importance of policy designs that flexibly account for local structural heterogeneity. Although centred on Iceland, the findings carry broader international relevance. The Icelandic EPR reform offers a unique, nationwide policy case for understanding how producer-funded recycling systems operate in small, geographically dispersed contexts, a situation shared by many island, Nordic, and peripheral regions. The identified dynamics between geography, seasonal population, and collection-system design illustrate structural challenges common across countries seeking to meet circular-economy targets under EPR frameworks. By combining Grey Relational and econometric analysis, the study also provides a methodological template for evaluating EPR performance where data are limited or uneven. These insights extend beyond Iceland, informing future design and assessment of harmonised producer-responsibility systems worldwide.

CRediT authorship contribution statement

Guðmundur Kristján Óskarsson: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sveinn Agnarsson:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Brynhildur Davíðsdóttir: Writing – review & editing, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Grammarly and Gemini/ChatGTP to improve the readability and language of this manuscript. The content in this manuscript is original input from the authors. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

Data availability

All data are available at the given sources.

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Research Paper

Source-separation infrastructure and the reduction of residual household waste: Evidence from Iceland's 2023 waste reform

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ABSTRACT

This study evaluates whether Iceland's 2023 waste-management reform, which combined Extended Producer Responsibility (EPR) financing with mandatory four-bin kerbside collection, reduced targeted household waste remaining in the general bin. Using a decade-long dataset (2014–2025) derived from systematic waste characterisation studies, the analysis employs a panel Interrupted Time Series (ITS) design comprising 55 observations across five analytical areas in the Capital Region to quantify changes in residual biodegradable waste, paper, plastic, and non-targeted fractions. The results indicate a statistically significant structural break in household disposal behaviour, with total waste in the general bin declining by an average of 37 % following the reform. This shift is primarily driven by a pronounced "organic transition," as biodegradable waste remaining in the residual stream decreased by 54 %. By 2024, total apparent capture rates for paper and plastic reached peaks of 83 % and 44 %, respectively, before showing slight stabilisation in 2025.

These findings suggest that the EPR framework provided an important financial and regulatory foundation, but the decisive behavioural mechanism was the rollout of accessible household-level source-separation infrastructure, especially for biodegradable kitchen waste. For paper and plastic, observed changes are more consistent with the continuation and reinforcement of pre-existing downward trends alongside improved post-reform apparent capture rates. However, the slight stabilisation in performance by 2025 is consistent with a tendency for initial participation gains to diminish over time, highlighting the importance of sustained behavioural engagement, contamination control, and complementary collection pathways for residual materials not targeted by the four-bin system.

1. Introduction

Transitioning to a circular economy is central to modern environmental policy (European Commission, 2020). While its theoretical benefits are well documented, implementing such systems in geographically isolated and demographically sparse nations presents unique challenges (Eisted & Christensen, 2011; Keske et al., 2018). With its sub-Arctic environment, high logistical costs, and reliance on imports, Iceland provides a useful case for examining how circular-economy policy is translated into household waste-management practice under spatial constraints. Historically, the Icelandic waste-management system has lagged behind its Nordic neighbours, characterised by a heavy reliance on landfilling and a fragmented, voluntary approach to recycling (Óskarsson et al., 2022).

The enactment of the Act on the Treatment of Waste (Act No. 55/2003) and the subsequent amendment introduced through the 2021 Waste Management Act (Act No. 103/2021), often referred to as the "Circular Law," marked a decisive shift in national strategy. Fully implemented from January 2023, the reform combined two linked but analytically distinct elements: a harmonised household collection mandate and an Extended Producer Responsibility (EPR) financing framework for packaging waste. In the Icelandic system, the EPR mechanism is primarily financial: producer and importer fees are administered through the Icelandic Recycling Fund and used to support

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the collection and processing of packaging waste, while municipalities remain responsible for organising collection services. The present study evaluates the material-flow effects of this reform on household residual waste composition; it does not estimate cost savings, municipal cost recovery, or the full distribution of costs between producers, municipalities, and households.

In the Icelandic context, the harmonised four-bin system mandates dedicated kerbside collection containers for four household fractions: (1) paper and cardboard, including both packaging and non-packaging printed paper; (2) plastic packaging; (3) biodegradable kitchen waste; and (4) mixed residual waste. This configuration should be understood as Iceland's national implementation of broader EU/EEA separate-collection obligations, rather than as a fixed EU-wide four-bin model. EU waste legislation requires the separate collection of key material streams, but the specific household bin configuration and collection-channel design vary between countries and municipalities. In this article, the terms harmonised and universal therefore refer to standardisation across Icelandic municipalities, not to a uniform European collection model.

Throughout this study, the receptacle for mixed residual waste is referred to as the general bin, roughly equivalent to "trash" or "garbage" in North American terminology. In European waste-policy terminology, residual waste refers to the mixed municipal waste fraction that remains after recyclable and biodegradable materials have been separated through dedicated collection systems. The term infrastructure therefore refers specifically to this household-level bin configuration and its associated kerbside collection services, rather than to downstream recycling plants or transport assets.

Other packaging materials covered by the EPR framework, such as glass bottles and metal cans, are not targeted by the kerbside four-bin system. These materials continue to be managed through neighbourhood drop-off containers and recycling centres. Prior to the 2023 reform, household source-separation arrangements were fragmented: all households had access to a general residual waste bin, but kerbside collection of paper and plastic varied between municipalities, and dedicated kerbside collection of biodegradable kitchen waste was largely absent. Recyclable materials were instead managed through a combination of voluntary municipal kerbside schemes, drop-off containers, and recycling centres. The reform therefore standardised access to household source-separation opportunities across municipalities, while retaining drop-off and recycling-centre channels as complementary infrastructure. Fig. 1 illustrates the shift from the typical pre-reform general-bin configuration to the post-reform household source-separation system, in which the four mandated fractions are commonly implemented through three physical containers. The dual-compartment container contains two physically separated internal chambers with independent collection compartments. Waste cannot move between the chambers during ordinary use; any cross-contamination would therefore result from incorrect household placement rather than mixing within the container.

While prior research has examined the cost and efficiency of Iceland's waste-management reforms (Óskarsson et al., 2022, 2025, 2026), the internal composition of the general bin remains unexplored. Evaluating apparent capture rates alone can be misleading without analysing residual waste composition, especially given confounding factors such as tourism seasonality (Arbulú et al., 2024), gross-weight contamination in separately collected fractions, and diminishing initial participation (Wilson et al., 2025). This study fills this gap through a granular, composition-based longitudinal analysis of Capital Region waste characterisation studies from 2014 to 2025. Focusing on the Capital Region, which encompasses approximately 64 % of the national population, allows the analysis to examine household separation behaviour under relatively stable, high-capacity collection conditions. While this regional focus excludes the most remote municipalities, it provides a robust setting for evaluating household behavioural change because it captures the clear majority of the Icelandic population while reducing confounding effects associated with extreme remoteness, service sparsity, and visitor-generated waste.

By applying Interrupted Time Series (ITS) analysis, we test whether the 2023 reform was associated with a structural break in household disposal behaviour. Because the reform was implemented as a policy bundle, including legal mandates, EPR financing, and household-level collection infrastructure, the ITS estimates should be interpreted as the combined effect of this reform package. The specific mechanism examined, however, is the physical rollout and operationalisation of the harmonised four-bin collection system at the household level. Specifically, we examine whether this infrastructural shift reduced the amount of biodegradable kitchen waste, paper, and plastic remaining in the residual household waste stream. Unlike prior studies that focused on municipal cost efficiency (Dijkgraaf & Gradus, 2015, 2020; Óskarsson et al., 2022, 2025) or aggregate recycling rates (Antonopoulos et al., 2021; Óskarsson et al., 2026), this article provides a granular examination of specific material fractions, offering the first composition-based longitudinal assessment of whether harmonised kerbside source-separation infrastructure can reduce the loss of targeted materials to residual household waste in a high-income island jurisdiction.



Fig. 1. Household waste collection infrastructure before and after Iceland's 2023 waste-management reform. Left: the typical pre-reform configuration, consisting primarily of a single general bin for mixed residual waste. Right: the post-reform four-bin system, which mandates the separation of four household fractions. For single-family and terraced homes, the system is frequently implemented using three physical wheeled bins to optimise space. These comprise a dual-compartment bin with two physically separated interior chambers for biodegradable kitchen waste (green label) and mixed residual waste (black label), a dedicated bin for plastic packaging (purple label), and a dedicated bin for the combined paper-and-cardboard fraction. On the latter bin, the orange label denotes cardboard and paperboard, while the blue label denotes newspapers and other paper. Both categories are placed in the same bin and constitute a single collection fraction. Note: Multi-family dwellings and apartment blocks typically use larger communal containers or other configurations for the same four fractions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Literature review

The effectiveness of waste management policies is contingent upon a complex interplay of infrastructure, economic incentives, and behavioural norms. This section reviews the theoretical and empirical literature underpinning EPR systems and household separation behaviour, with a specific focus on the unique constraints of remote, island economies.

2.1. Extended producer responsibility and policy instruments

Extended Producer Responsibility (EPR) shifts post-consumer waste management burdens from municipalities to producers, incentivising eco-design and funding collection and recycling systems (Joltreau, 2022; Rodrigues et al., 2016). In practice, however, EPR should be distinguished from the household collection interface. EPR can create the financial and institutional conditions needed to expand services, but producer responsibility alone does not necessarily change household separation behaviour unless residents are given accessible and understandable source-separation opportunities. This distinction is particularly important in the Icelandic case, where the EPR framework finances packaging-waste management but municipalities remain responsible for operating collection services. The reform therefore provides a useful case for examining whether financial regulation translates into behavioural change through improved kerbside convenience. The debate in the literature often centres on the efficacy of economic instruments (e.g., unit-based pricing or "Pay-As-You-Throw") versus physical infrastructure (convenience). Dijkgraaf & Gradus (2015) argue that while unit-based pricing is cost-effective, its environmental impact can be limited if not paired with accessible source-separation options. Conversely, Andersson & Stage (2018) provide compelling evidence from Sweden that the introduction of separate food waste collection infrastructure is a more powerful driver of diversion than weight-based tariffs alone. This supports the "infrastructure-first" hypothesis, suggesting that minimising the physical effort of source separation and reducing the "distance to bin" is a prerequisite for effective pricing mechanisms (Struk, 2017; Xirogiannopoulou et al., 2024).

2.2. The "Organic Revolution" and plastic diversion

A central component of the circular transition is the diversion of biodegradable waste, which poses environmental risk in landfills due to methane emissions. The literature emphasises that organic waste separation is highly sensitive to convenience and system design (Andersson & Stage, 2018). Furthermore, the quality of separated fractions is critical; contamination in plastic streams, for instance, can negate the benefits of recycling (Dijkgraaf & Gradus, 2020). EU-level material flow analyses show that, even in mature source-separation systems, plastic packaging recovery rates remain substantially lower than those of paper, reflecting polymer heterogeneity, sorting losses, and downstream processing constraints rather than a lack of household participation (Antonopoulos et al., 2021). For Iceland, where plastic packaging demand is high but recycling infrastructure has historically been immature (Mager et al., 2022; Ögmundarson et al., 2022), the transition to a mandatory collection system therefore presents both a logistical challenge and a significant opportunity to close the material loop.

However, the persistence of these new separation habits is not guaranteed. Wilson et al. (2025) and Trushna et al. (2024) highlight the role of behavioural interventions and the tendency for participation gains to diminish over time, whereby participation may initially increase following system introduction but subsequently decline as the intervention becomes routine. This phenomenon necessitates longitudinal monitoring rather than static snapshots of performance.

2.3. The context of remoteness and seasonality

Waste management in Iceland operates under structural conditions distinct from those typically observed in continental Europe, despite the country's obligation to implement EU waste legislation through the European Economic Area (EEA) framework. First, the "tyranny of distance" in Arctic and sub-Arctic regions creates diseconomies of scale for waste collection and transport (Eisted & Christensen, 2011; Keske et al., 2018; Sebastian & Louis, 2022). These spatial constraints increase operational costs and complicate the provision of uniform collection services, particularly outside dense urban areas. Second, the intense seasonality of tourism exerts additional pressure on waste infrastructure. Arbulú et al. (2024) and Caponi (2022) demonstrate that tourism flows can distort per-capita waste generation statistics, making it difficult to disentangle resident behaviour from visitor impacts. In Iceland, where tourist arrivals significantly exceed the resident population, analysing waste composition within residential collection routes, rather than relying on aggregate municipal waste statistics, is therefore essential for accurately measuring changes in household disposal behaviour.

3. Methodology

3.1. Data sources and sampling strategy

This study uses systematic waste characterisation data from (SORPA, n.d.), the Capital Region's waste management authority. This region comprises six constituent municipalities (Reykjavík, Kópavogur, Hafnarfjörður, Garðabær, Mosfellsbær, and Seltjarnarnes). It contains approximately 64 % of the national population and represents the largest and most comprehensive municipal waste management system in the country. As such, it provides an appropriate setting for examining structural changes in household waste composition.

The analysis is based on a longitudinal dataset covering the period 2014–2025. Waste characterisation was conducted through repeated manual sampling of residual household waste collected from general bins. During each sampling campaign, individual subsamples of approximately 100 kg were collected and manually sorted into predefined material categories. All manual sorting and weighing were conducted on an "as received" basis (wet weight), reflecting the operational characteristics of municipal solid waste collection systems. No drying or moisture correction procedures were applied prior to weighing. To reduce sampling uncertainty and natural variation in waste generation, annual sampling campaigns consisted of 24–30 independently collected subsamples distributed across municipalities in proportion to population size. The resulting observations were subsequently analysed within a spatial panel framework to improve statistical power and account for variation between analytical areas. During the manual sorting process, materials were classified according to their dominant recoverable material type. Where feasible, minor surface contamination was removed prior to classification. However, items that were heavily contaminated, unrecoverable, or inseparable from adhering contaminants (e.g., heavily grease-soiled paper products) were assigned to the category "Non-targeted Fractions" rather than to recyclable material streams. The original waste characterisation protocol employed by SORPA is substantially more granular than the categories used in the present analysis, classifying waste into more than 30 detailed subfractions that are typically reported within approximately 15 broader material groups. For the purposes of evaluating the behavioural effects of the four-bin collection system, these detailed categories were consolidated into four analytical fractions: biodegradable kitchen waste, paper, plastic, and non-targeted fractions. The "non-targeted fractions" category encompasses all materials not directly targeted by the kerbside paper, plastic, or kitchen biodegradable waste collection systems, including sanitary products, textiles, clothing, non-kitchen organic waste, garden waste, deposit beverage containers, glass, metals,

hazardous waste, and miscellaneous residual materials such as vacuum cleaner bags. Although no formal contamination threshold was applied, this protocol reduced the risk of substantially contaminated materials artificially inflating the measured paper and plastic fractions within the residual waste composition analysis.

The number of samples collected annually ranged from 24 to 30, distributed proportionally according to the size of the municipalities, with Reykjavík accounting for approximately half of the samples each year. To minimise the confounding effects of seasonal variation in household waste generation, waste characterisation campaigns were conducted consistently during the autumn months throughout the study period, predominantly in November and occasionally commencing in late October. This temporal consistency enhances the comparability of waste composition observations before and after the 2023 reform. While seasonal effects cannot be entirely excluded, the alignment of sampling periods reduces the likelihood that observed changes are attributable to seasonal fluctuations rather than underlying behavioural or system-level changes. To ensure statistical reliability and maintain a minimum of two samples per observational unit, the region's two smallest municipalities, Mosfellsbær and Seltjarnarnes, were combined into a single analytical unit using a weighted average based on population size and waste quantities. The final dataset, therefore, consists of five analytical areas within the Capital Region: Reykjavík, Kópavogur, Hafnarfjörður, Garðabær, and the combined Mosfellsbær–Seltjarnarnes area. Sampling was temporarily suspended in 2020 due to the COVID-19 pandemic, resulting in a single missing year in the time series.

Once the material composition shares were determined from the sorted samples, these percentages were combined with data from SORPA on the total quantities of residual household waste collected from general bins in each municipality. This allowed the estimation of kg per capita of specific waste fractions in the residual waste stream, calculated separately for each municipality and year.

Within the organic fraction, this study focuses exclusively on kitchen biodegradable waste, excluding other organic fractions such as garden waste, pet waste, and other biodegradable materials. Throughout this article, the terms "biodegradable waste" and "organic waste" are used interchangeably to refer to kitchen food waste, which constitutes the primary target of the separate organic collection system introduced in 2023. This restriction is applied because the new household organic bins are primarily intended for kitchen waste, allowing for a more precise measurement of the specific separation behaviour targeted by the 2023 introduction of separate organic collection.

The introduction of the new four-bin household collection system, including the separate collection of organic waste, was rolled out in the Capital Region between mid-May and mid-September 2023. The waste characterisation sampling for 2023 was conducted subsequently in October and November, capturing the post-implementation environment.

To ensure that annual estimates accurately reflected this mid-year transition, the per-capita waste quantities for 2023 were calculated using a split approach. Waste generated prior to the rollout was estimated using composition percentages from the previous year's characterisation study, while waste generated after the implementation was estimated using the material composition observed in the late-2023 sampling. The annual 2023 estimate, therefore, represents a weighted combination of pre-implementation and post-implementation waste composition, weighted proportionally by the total waste volumes recorded under each regime. While this split estimation provides the most robust quantitative approximation of the transition year, it inherently assumes that household separation behaviour remained static under the old regime. Consequently, this approach does not account for potential anticipatory behavioural shifts, such as increased use of drop-off centres, that may have been driven by pre-rollout public awareness campaigns prior to the physical deployment of the bins.

From 2024 onward, the four-bin system was fully operational across the region, and waste composition estimates are based entirely on post-implementation sampling. Consequently, 2023 represents a transition year in the time series, while the years 2024–2025 reflect the first full years of operation under the new collection system.

To calculate material-specific apparent capture rates, separately collected quantities must be compared with the estimated amounts remaining in the residual waste stream. To achieve this, information on separately collected packaging waste was obtained from (Úrvinnslusjóður, n.d.), the Icelandic Recycling Fund, which reports the total quantities of paper and plastic collected through kerbside collection, drop-off containers, and recycling centres. While drop-off containers and recycling centres primarily serve households, an unquantifiable portion of the paper and plastic collected at these locations inevitably originates from small commercial enterprises utilising public infrastructure. As a result, aggregate collection volumes for these channels may overstate pure household generation. Because pre-2023 historical data from voluntary and fragmented collection channels are not fully comparable to post-reform figures, calculating consistent decade-long longitudinal apparent capture rates is unfeasible. This data limitation underscores the methodological necessity of relying on the material composition of the residual general bin, which has been consistently sampled since 2014, as the most robust and continuous proxy for evaluating shifts in household separation behaviour.

3.2. Longitudinal structure and apparent capture rate calculation

The analysis covers the period from 2014 to 2025, allowing for the examination of medium-term trends before and after the implementation of the 2023 reform. As previously noted, detailed waste characterisation by material fraction is unavailable for 2020; however, total waste quantities in the general bin were recorded, preserving continuity in the aggregate time series. For analytical purposes, the timeline is divided into a pre-reform period (2014–2022) and a post-reform period (2023–2025).

Apparent total capture rates are computed as the ratio of separately collected material to the sum of separately collected material and material remaining in the general bin. Apparent total capture rates were calculated as the quantity collected separately through kerbside collection, drop-off containers, and recycling centres divided by the estimated total material quantity:

$$\text{Apparent total capture rate} = \frac{K + D}{K + D + G} \tag{1}$$

where K represents kerbside collection, D represents collection through drop-off containers and recycling centres, and G represents the estimated quantity remaining in the general bin.

To describe the relative contribution of each collection and disposal channel in Fig. 4, kerbside, drop-off/centre, and general-bin shares were calculated using the same estimated total material quantity as the denominator:

$$\begin{aligned}\text{Kerbside share} &= \frac{K}{K + D + G},\ \text{Drop} - \text{off} \Big/ \text{centre share} \\ &= \frac{D}{K + D + G},\ \text{General} - \text{bin share} = \frac{G}{K + D + G}\end{aligned} \tag{2}$$

The previously used kerbside apparent capture measure, which excluded drop-off and recycling-centre collection from the denominator, was removed because it could obscure the continuing contribution of these complementary collection channels. These measures provide an operational indicator of the extent to which recyclable materials are diverted from the general bin under the four-bin system.

Because the aggregate weights of separately collected fractions were not manually sorted to isolate moisture and non-targeted contributions (contamination), the metric is referred to throughout this study as an apparent capture rate. This terminology acknowledges that the estimates are derived from gross collected weights and do not adjust for contamination, moisture, or non-target material contributions.

Consequently, the apparent capture rates reported here should be interpreted as operational indicators of diversion performance rather than purity-adjusted material recovery rates. Similar concerns regarding contamination in separately collected packaging streams have been documented by Schuch et al. (2023) and Thoden Van Velzen et al. (2019).

Although the overall time series spans more than a decade, the chronological post-reform period currently includes three annual observations (2023–2025). Standard interrupted time series guidelines typically recommend a minimum of 8 to 12 data points before and after an intervention to reliably estimate regression coefficients (Penfold & Zhang, 2013; Wagner et al., 2002). However, there are no fixed limits regarding the number of data points, as statistical power also depends heavily on the variability within the data and the strength of the intervention's effect (Lopez Bernal et al., 2016). By structuring the data as a spatial panel across five analytical areas, this study yields 40 pre-reform and 15 post-reform observations, effectively surpassing these conventional minimums to provide sufficient statistical power. While the adoption of this spatial panel structure bolsters the overall statistical power of the analysis, the relatively short post-intervention chronological window means that inferential weight remains primarily on immediate level shifts, though pronounced gradual slope changes can still be detected.

3.3. Interrupted time series (ITS) analytical framework

To evaluate whether the 2023 reform is associated with statistically significant changes in residual waste disposal, the study employs a Panel Interrupted Time Series (ITS) design using segmented regression with municipality fixed effects. ITS is a quasi-experimental method widely used in policy evaluation when randomised control designs are infeasible, and when an intervention occurs at a clearly defined point in time (Linden, 2015; Lopez Bernal et al., 2016; Wagner et al., 2002; Wooldridge, 2020).

Transitioning from an aggregate time series to a spatial panel dataset (comprising five geographical areas observed from 2014 to 2025) increases the effective number of observations and improves statistical power. Furthermore, incorporating a panel structure allows the model to explicitly control for unobserved, time-invariant baseline differences between municipalities, such as distinct housing structures or localised socio-demographic factors, that might otherwise confound the results (Wooldridge, 2020).

The segmented panel regression model is specified as:

$$Y_{it} = \beta_0 + \beta_1 T_t + \beta_2 D_t + \beta_3 P_t + \mu_i + \varepsilon_{it} \quad (3)$$

where Y_{it} denotes per-capita residual waste in municipality i in year t; T_t is a continuous time variable capturing the pre-reform baseline trend; D_t is a binary indicator taking the value 0 before 2023 and 1 thereafter, representing the immediate level change (step change) associated with the reform; and P_t is a continuous time-since-intervention variable defined as 0 for all years prior to 2023 and increasing sequentially thereafter (1 for 2023, 2 for 2024, etc.), capturing the change in slope following the reform. The term μ_i represents the municipality fixed effect, and the error term ε_{it} captures unexplained variation (Wooldridge, 2020). Municipality fixed effects control for time-invariant structural characteristics such as housing density, infrastructure configuration, and socio-demographic composition.

Separate Panel ITS models are estimated for total waste in the general bin, kitchen biodegradable waste, paper, plastic, and non-targeted fractions. Estimating models by waste stream allows the analysis to identify heterogeneous behavioural responses to the reform across material categories with differing collection requirements and separation complexities. To maintain consistent model specifications across all waste fractions, the year 2020 was omitted from the regression analyses. The models are therefore estimated as an unbalanced spatial panel. Because panel data frequently violate standard Ordinary Least Squares (OLS) assumptions regarding independent and identically distributed errors, comprehensive diagnostic testing was performed. The Breusch-Pagan test was utilised to assess heteroscedasticity (non-constant variance across municipalities), while the Durbin-Watson statistic was calculated to assess first-order serial autocorrelation (Wooldridge, 2020).

Diagnostic testing indicated the presence of heteroscedasticity in several models. To ensure valid statistical inference and avoid inflated test statistics, all models were therefore estimated using heteroscedasticity and autocorrelation consistent (HAC) standard errors (Wooldridge, 2020). This robust estimation approach adjusts the standard errors and p-values to account for heteroscedasticity and serial autocorrelation in the regression residuals.

All statistical analyses were conducted using the R statistical computing environment (R Foundation for Statistical Computing, n.d.). Standard linear regression functions with factor variables (the Least Squares Dummy Variable approach) were used to estimate the fixed-effects models, while the lmtest and sandwich packages were employed to calculate the robust HAC standard errors.

4. Results and discussion

4.1. Structural changes in residual waste and the organic transition

Table 1 reports the average per-capita amount of waste disposed in the general bin across the five analytical areas before (2014–2022) and after (2023–2025) the implementation of the 2023 reform.

Across all residual fractions, the results show a substantial reduction in material remaining in the general bin following the reform. Total waste in the general bin declined 37 % (144.9 to 91.4 kg/capita/year). Biodegradable waste showed the largest decrease (54 %, 61.8 to 28.4 kg/capita/year), while plastic and paper fell by 42 %, respectively. In contrast, non-targeted fractions declined only marginally (−6 %, 41.6 to 39.1 kg/capita/year).

Fig. 2 illustrates the temporal development of total waste in the general bin from 2014 to 2025, disaggregated into biodegradable waste, paper, plastic, and non-targeted fractions.

Fig. 3 presents the proportional composition of the general bin over the same period.

Prior to the reform, total waste in the general bin remained relatively stable (135–155 kg/capita/year), with biodegradable waste constituting the largest fraction throughout the period. Notably, even during the societal disruptions associated with the COVID-19 pandemic (2020–2021), per-capita residual waste levels showed only modest variation. This temporal stability suggests that the pronounced decline observed from 2023 onward is unlikely to reflect broader macroeconomic or societal shocks alone and is instead consistent with the timing of the 2023 policy reform and the introduction of separate collection infrastructure. Following the reform, total residual waste declined sharply, falling from 135 kg/capita in 2022 to 82 kg/capita in 2024, before stabilising at 88 kg/capita in 2025.

Table 1
Average per-capita waste in the general bin before and after the 2023 reform.

Waste Stream	Pre-Reform Mean (2014–22) (kg/capita/year)	Post-Reform Mean (2023–25) (kg/capita/year)	Average Reduction (%)
Total waste in the general bin	144.9	91.4	−37 %
Biodegradable Waste	61.8	28.4	−54 %
Paper	15.8	9.1	−42 %
Plastic	25.7	14.8	−42 %
Non-targeted Fractions	41.6	39.1	−6 %

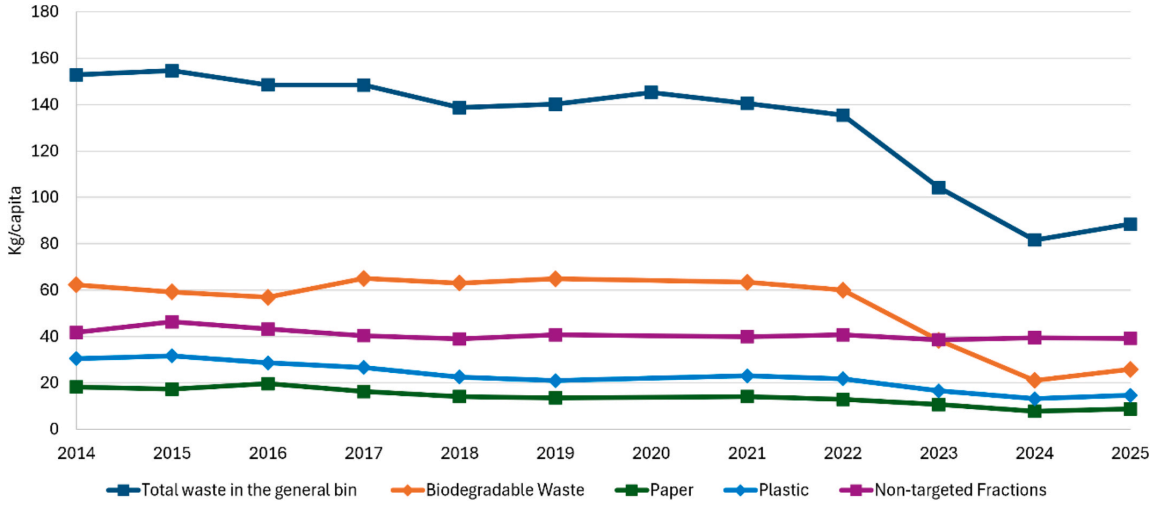


Fig. 2. Total waste in the general bin (kg/capita) and its material composition (biodegradable waste, paper, plastic, and non-targeted fractions).

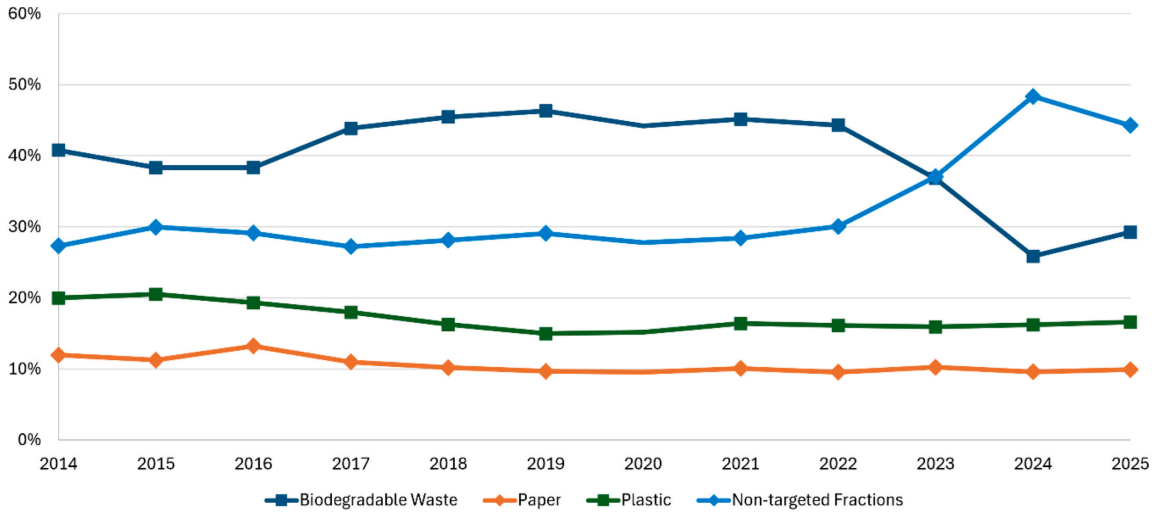


Fig. 3. Proportional composition of the general bin by material fraction.

The reform's impact was highly concentrated; approximately two-thirds of the total waste decline in the general bin is attributed to biodegradable waste alone, highlighting the pivotal role of the new organic waste collection system. The sharp decline following implementation suggests that the introduction of dedicated household organic collection successfully removed a major barrier to diversion, supporting the infrastructure-first hypothesis (Andersson & Stage, 2018; Struk, 2017).

Importantly, the trajectory of non-targeted fractions provides a useful internal comparator. Despite the broad regulatory scope of the 2023 "Circular Law," the aggregate reduction in other waste quantities was comparatively marginal (−6 %). This reflects the fact that these materials are either not fully covered by existing collection schemes or are inherently difficult to divert. As biodegradable waste was diverted, the general bin became increasingly dominated by these heterogeneous residual materials.

4.2. Segmented regression analysis of reform effects

Table 2 presents the results of the Panel Interrupted Time Series (ITS) segmented regression models, estimating changes in the amount of waste disposed in the general bin.

The Durbin–Watson statistics are reported as descriptive diagnostics of first-order residual autocorrelation. Because several statistics departed from the benchmark value of approximately 2, and because residual dependence could not be excluded, HAC standard errors were applied consistently across all models. The statistical significance reported for the regression coefficients is based exclusively on the HAC-adjusted coefficient tests.

The ITS results confirm the principal descriptive patterns. For total waste in the general bin, the reform was associated with a highly significant immediate level reduction of 42.66 kg/capita ($p < 0.001$). Biodegradable kitchen waste exhibited the largest reform effect, with an

Table 2
Panel interrupted time series regression results for waste in the general bin (2014–2025).

Variable	Total Waste in General bin	Biodegradable Waste	Paper	Plastic	Non-targeted Fractions
Intercept β_0	162.15***	59.45***	21.09***	35.60***	46.20***
Time Trend β_1	−1.49***	0.56	−0.87***	−1.43***	0.08
Reform Level β_2	−42.66***	−31.31***	−1.59	−4.02*	−4.15*
Post-Slope Change β_3	−6.71	−5.87*	−0.12	0.29	−0.84
R-squared (R^2)	0.95	0.85	0.80	0.63	0.35
D-W statistic	1.362	1.287	2.406	1.629	1.755

Note: Statistical significance of the regression coefficients is based on heteroscedasticity- and autocorrelation-consistent (HAC) standard errors: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

immediate level reduction of 31.31 kg/capita ($p < 0.001$). The post-reform slope change was also statistically significant (−5.87 kg/capita/year, $p < 0.05$), indicating an additional decline in biodegradable waste remaining in the general bin following implementation.

For paper and plastic, the significant negative pre-reform time trends indicate that the quantities of these materials remaining in the general bin were already declining before the legislative mandate. Plastic exhibited a statistically significant immediate level reduction following the reform ($\beta_2 = -4.02$ kg/capita, $p < 0.05$), but no significant post-reform slope change. Paper showed neither a statistically significant reform-related level change nor a significant post-reform slope change. These results suggest that the four-bin system reinforced and standardised an existing downward trajectory for paper and plastic rather than initiating an entirely new pattern. As discussed in Section 4.1, the pre-existing trends may reflect a combination of expanding voluntary collection, increasing household familiarity with source separation, declining printed-paper consumption, and packaging lightweighting.

Finally, non-targeted fractions exhibited a statistically significant immediate level reduction of 4.15 kg/capita ($p < 0.05$) coinciding with the reform. However, the absence of a significant post-reform slope change indicates that the reform was not associated with a continuing decline in these materials after the initial adjustment.

4.3. Material-specific apparent capture rates and collection-channel distribution

Table 3 reports the underlying per-capita quantities of biodegradable waste, paper, and plastic collected through kerbside services and drop-off facilities or remaining in the general bin. These absolute quantities complement the proportional distribution shown in Fig. 4 and allow the relative contribution of each collection channel to be interpreted alongside the magnitude of the material flows.

Table 3
Per-capita quantities of biodegradable waste, paper, and plastic by collection and disposal channel, 2023–2025.

Year	Collection channel	Biodegradable Waste (kg/capita)	Paper (kg/capita)	Plastic (kg/capita)
2023	Kerbside collection	13.9	18.8	5.5
	Drop-off/Centres		15.1	2.7
	Remaining in General Bin	38.4	10.7	16.6
	Estimated total material quantity	**52.3**	**44.6**	**24.8**
2024	Kerbside collection	27.2	24.1	8.6
	Drop-off/Centres		13.4	1.7
	Remaining in General Bin	21.1	7.8	13.2
	Estimated total material quantity	**48.3**	**45.3**	**23.5**
2025	Kerbside collection	29.0	23.2	8.3
	Drop-off/Centres		13.7	1.9
	Remaining in General Bin	25.9	8.8	14.7
	Estimated total material quantity	**54.9**	**45.7**	**24.9**

Notes: Estimated total material quantity is the sum of kerbside collection, drop-off containers and recycling centres, and the estimated quantity remaining in the general bin. Biodegradable kitchen waste was collected exclusively through kerbside collection in the data used for this analysis; therefore, no drop-off quantity is reported. Values may differ slightly from calculated apparent capture percentages because of rounding.

The transition from 2023 to 2024 partly reflects the movement from a partial implementation year to the first full year of operation. For biodegradable waste, kerbside collection increased from 13.9 kg/capita in 2023 to 27.2 kg/capita in 2024, while the amount remaining in the general bin declined from 38.4 to 21.1 kg/capita. In 2025, kerbside collection increased slightly to 29.0 kg/capita, although biodegradable waste remaining in the general bin rose to 25.9 kg/capita.

For paper and plastic, kerbside collection was the largest separate collection channel, but drop-off containers and recycling centres continued to make an important contribution, particularly for paper. In 2025, 23.2 kg/capita of paper was collected through kerbside services and 13.7 kg/capita through drop-off containers and recycling centres. The latter therefore remained a substantial component of the paper collection system rather than a marginal residual channel.

Fig. 4 presents the proportional distribution of each material across kerbside collection, drop-off containers and recycling centres, and the general bin. Combining the two separate-collection channels, total apparent capture rates were 27 %, 56 %, and 53 % for biodegradable waste; 76 %, 83 %, and 81 % for paper; and 33 %, 44 %, and 41 % for plastic in 2023, 2024, and 2025, respectively. The clearest redistribution occurred for biodegradable waste. The share remaining in the general bin declined from 73 % in 2023 to 44 % in 2024, while the kerbside share increased correspondingly from 27 % to 56 %. In 2025, the kerbside share moderated to 53 %, indicating some stabilisation after the initial implementation period.

Paper showed the strongest overall separation performance. The share remaining in the general bin declined from 24 % in 2023 to 17 % in 2024 and remained below one-fifth in 2025. Importantly, this high level of separation resulted from the combined contribution of kerbside and drop-off collection. Drop-off containers and recycling centres accounted for approximately 30–34 % of the estimated paper quantity throughout the period, confirming that these facilities continued to play a substantial complementary role after the introduction of harmonised kerbside collection.

Plastic showed a more limited redistribution. Although the share remaining in the general bin declined from 67 % in 2023 to 56 % in 2024, it increased slightly to 59 % in 2025. Kerbside collection accounted for approximately one-third of the estimated plastic quantity in 2024 and 2025, while drop-off facilities contributed a further 7–8 %. Thus, even after implementation of the four-bin system, most estimated plastic packaging remained in the general bin.

The difference between paper and plastic likely reflects variation in both material characteristics and household separation behaviour. Paper and cardboard are comparatively homogeneous and generally easy for households to recognise. Plastic packaging, by contrast, includes a wider range of sizes, formats, polymers, and household uses. Larger and more conspicuous items, such as bottles and containers, may be separated relatively consistently, whereas small, lightweight,

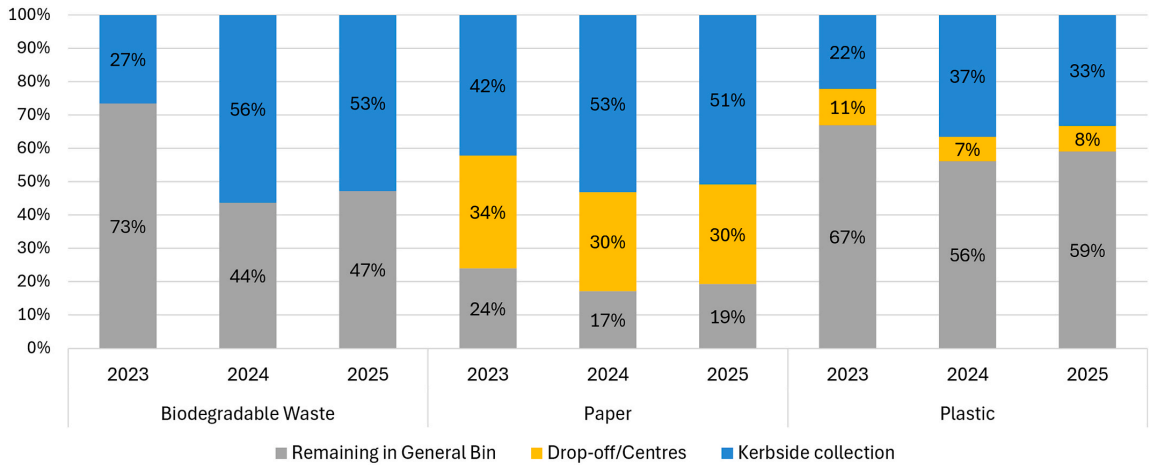


Fig. 4. Distribution of biodegradable waste, paper, and plastic across collection and disposal channels, 2023–2025. Note: Percentages represent each channel's share of the estimated total quantity of the relevant material. Because biodegradable kitchen waste was collected exclusively through kerbside collection in the data used here, no drop-off contribution is shown for this material. Percentages may not sum to exactly 100 % because of rounding.

contaminated, or less salient items, including wrappers and packaging generated in kitchens and bathrooms, are more likely to remain in the general bin. The lower separation of plastic may therefore reflect uneven household participation across packaging types, together with contamination and downstream processing constraints, rather than a general absence of household participation (Antonopoulos et al., 2021; Dijkgraaf & Gradus, 2020; Thoden Van Velzen et al., 2019).

4.4. Behavioural dynamics, stabilisation, and policy implications

Although the reform was associated with an immediate reduction in residual waste, the slight increase in total waste in 2025 suggests an early stabilisation following the initial adjustment period. This pattern is consistent with the possibility that initial participation gains may moderate as a newly introduced collection system becomes embedded in everyday routines (Trushna et al., 2024; Wilson et al., 2025).

The persistence of substantial material remaining in the general bin, particularly non-targeted fractions and remaining recyclable materials, suggests that household-level four-bin infrastructure alone cannot fully eliminate the disposal of targeted materials in residual household waste. This should not be interpreted as evidence that drop-off systems should simply be replaced by kerbside collection. Rather, the results indicate that once convenient kerbside access has been provided for the main targeted fractions, further improvements depend increasingly on complementary measures. These include targeted communication, feedback mechanisms, social-norm reinforcement, contamination control, and continued improvement of complementary drop-off and recycling-centre pathways for materials not directly targeted by the four-bin system (Trushna et al., 2024; Wilson et al., 2025). At the same time, further reductions in the "non-targeted fractions" category are unlikely to be achieved through behavioural reinforcement alone. They may require additional or better-designed collection pathways for materials not targeted by the four-bin system, such as textiles, e-waste, glass, metals, hazardous waste, bulky waste, and non-kitchen organic fractions.

From a broader perspective, the magnitude and speed of the observed reductions substantially revise expectations regarding Iceland's trajectory towards European landfill-reduction targets. Earlier assessments projected slow convergence under a voluntary regime (Óskarsson et al., 2022, 2025); the structural shift identified here demonstrates that harmonised regulation combined with universal infrastructure can compress this timeline considerably, even in a high-income system operating under pronounced logistical constraints. In this sense, the 2023 reform represents not only a compliance mechanism but a credible pathway for accelerating circularity in structurally constrained waste systems.

5. Limitations

Several limitations of this study should be acknowledged. First, the analysis focuses on the Capital Region of Iceland, which benefits from relatively dense settlement patterns and high-capacity waste collection infrastructure. The results may not fully generalise to more remote or sparsely populated regions where logistical constraints are more pronounced.

Second, the study employs a spatial panel Interrupted Time Series design comprising 55 observations across five geographical areas. While this approach increases statistical power and controls for time-invariant differences between municipalities, causal attribution remains complex in the presence of a "policy shock" where legal mandates and infrastructure rollouts occur simultaneously.

Third, although tourism seasonality is a known driver of municipal waste generation in Iceland, the stability of foreign visitor arrivals between 2023 and 2025, which remained nearly static at approximately 2.2 million annually (Hagstofa Íslands, n.d.), suggests that visitor flows are unlikely to have materially distorted the post-reform longitudinal trends. By specifically analysing residential collection routes, this research further minimises the confounding effects of visitor-generated waste compared to aggregate municipal data.

Fourth, waste characterisation data were unavailable for 2020 due to pandemic-related disruptions. While total waste in general bin quantities were recorded for that year, preserving continuity in the overall time series, the absence of material-specific composition data for 2020 introduces minor uncertainty into the precise estimation of long-term compositional trends.

A significant methodological limitation concerns the calculation of apparent capture rates for separately collected fractions, particularly paper and plastic packaging. Because the separately collected streams were not manually characterised, the estimates are derived from gross collected weights and do not adjust for contamination, moisture, or non-target material contributions. As documented in previous research (Schuch et al., 2023; Thoden Van Velzen et al., 2019), contamination levels in separately collected packaging streams can vary substantially

across collection systems and jurisdictions. The apparent capture rates reported here should therefore be interpreted as operational indicators of diversion performance rather than purity-adjusted material recovery rates. Importantly, the primary findings of this study are based on the composition analysis of the residual waste stream and the interrupted time series results, which rely on manually sorted waste characterisation data and are therefore substantially less sensitive to these measurement issues.

A related limitation concerns the interpretation of the pre-reform decline in paper and plastic in the general bin. The ITS models identify statistically significant downward trends before 2023, but the available data do not allow these trends to be decomposed into separate drivers such as expanded voluntary recycling access, changing household norms, changes in material consumption, or packaging lightweighting. Consequently, the paper and plastic results should be interpreted as evidence that the reform reinforced an existing trajectory, rather than as a definitive explanation of why that trajectory began.

Finally, although sampling was conducted consistently during the autumn months throughout the study period to maximise temporal comparability, waste composition can exhibit seasonal variation associated with consumption patterns, holidays, and weather conditions. Consequently, some year-to-year variation may reflect residual seasonal influences that are not fully captured by the study design. However, the consistent use of an autumn sampling window reduces the likelihood that the observed post-2023 changes are primarily attributable to seasonal effects.

6. Conclusion

Iceland's 2023 waste-management reform represents a major shift toward a household collection system associated with rapid reductions in waste remaining in the general bin. Using a panel ITS design on a decade-long dataset from the Capital Region, this study finds that the combination of a mandatory four-bin system and harmonised EPR financing coincided with a structural break in household disposal behaviour. Notably, the reform was associated with an immediate and substantial reduction in residual household waste, driven primarily by a more than 50 % decline in biodegradable material remaining in the general bin. This rapid shift suggests that the provision of dedicated collection infrastructure may unlock substantial diversion potential where a major waste fraction previously lacked a separate collection pathway. The finding aligns with evidence from other Nordic contexts, where separate household collection systems have proven more effective at diverting organic waste than economic incentives alone (Andersson & Stage, 2018).

In contrast, the interrupted time-series models indicate that reductions in paper and plastic remaining in the general bin largely represented the continuation and reinforcement of trends already underway before the reform. These trends may reflect a combination of expanding voluntary collection services, increasing household familiarity with source separation, declining use of printed paper, and packaging lightweighting. The reform appears to have standardised and reinforced this existing trajectory rather than initiating an entirely new pattern. This distinction highlights the importance of accounting for both pre-existing behavioural developments and changes in material consumption when evaluating collection-system interventions.

At the same time, the results point to clear limits of infrastructure-led reform. While paper achieved consistently high total apparent capture rates, plastic performance remained substantially lower. The results suggest that separation varies across plastic-packaging formats: larger and more conspicuous items may be separated relatively consistently, whereas small, lightweight, contaminated, or less salient packages are more likely to remain in the general bin. Contamination and downstream processing constraints may further limit recovery (Antonopoulos et al., 2021; Dijkgraaf & Gradus, 2020; Thoden Van Velzen et al., 2019). Moreover, early signs of stabilisation in apparent capture rates suggest that the largest gains may occur during the initial implementation phase, with subsequent improvements becoming increasingly incremental as new separation practices become embedded in everyday routines.

Taken together, these findings suggest that infrastructure remains a necessary but not sufficient condition for advancing circular economy objectives. While universal separate collection can support rapid and substantial improvements in material diversion, particularly for organic waste, achieving further gains may increasingly depend on addressing material-specific recovery constraints, improving recycling system performance, and sustaining long-term household engagement.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used Grammarly and Gemini/ChatGPT to improve the readability and language of this manuscript. The content in this manuscript is original input from the authors. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Guðmundur Kristján Óskarsson: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sveinn Agnarsson:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Brynhildur Davíðsdóttir:** Writing – review & editing, Supervision. **Helgi Thor Ingason:** Writing – review & editing, Supervision.

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.

Data availability

All data are available at the given sources.

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