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Research article

Influence of Canadian provincial stewardship model attributes on the cost effectiveness of e-waste management

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ABSTRACT

This paper presents a comprehensive analysis of e-waste collection and management trends across six Canadian provinces, focusing on e-waste collection rates, provincial stewardship model attributes, program strategies and budget allocations from 2013 to 2020. Temporal and regression analyses were conducted using data from Electronic Product Recycling Association reports. A group characterization based on geographical proximity is proposed, aiming to explore the potential outcomes of fostering collaboration among neighboring provinces. The analysis emphasizes the significant impact of stewardship model attributes on e-waste collection rates, with Quebec emerging as a standout case, showcasing a remarkable 61.5% surge in collection rates. Findings from group analysis reveal a positive correlation between per capita e-waste collection rate and the growth of businesses and collection sites in Western Canada (Group A - British Columbia, Saskatchewan, and Manitoba). This highlights the potential benefits of a coordinated waste management approach, emphasizing the importance of shared resources and collaborative policies. Saskatchewan and Manitoba allocated only 6.6% and 7.0% of their respective budgets to e-waste transfer and storage. British Columbia's observed steady decrease of e-waste collection rate. In Group A, stewards handled 2.18–13.95 tonnes of e-waste during the study period. The cost per tonne of e-waste tended to be lower when more e-waste is managed per steward, suggesting the potential benefits of an integrated e-waste collection and management system.

1. Introduction and literature review

In recent years, the rapid advancement of technology has led to frequent updates and replacements of electronic devices, which has contributed to the generation of a significant and rapidly growing amount of electronic waste, or e-waste. E-waste is regarded as a category of waste that is expanding quickly on a global scale (Baldé et al., 2017; Boubellouta and Kusch-Brandt, 2021; Pan et al., 2022), making its management a critical concern. According to recent estimates by the United Nations, approximately 53.6 million metric tonnes (Mmt) of e-waste was generated globally in 2019 (Forti et al., 2020), a dramatic increase from just over 41.8 Mmt in 2014 (Baldé et al., 2015). The Global E-waste Monitor forecasted a potential 74.7 Mmt of e-waste by 2030 and up to 110 Mmt by 2050, if no stringent action is taken (Forti et al., 2020). Even though the global e-waste generation rate is outpacing the global population growth rate, only a small portion is being properly recycled. Only 20% (8.9 Mmt) of e-waste was documented to be collected and properly recycled worldwide in 2016, which then declined to 17.4% in 2019 (Baldé et al., 2017; Ghimire and Ariya, 2020; Van Yken et al., 2021). The USA and Canada are among the top generators of e-waste. According to recent studies, e-waste generation per capita in Canada has increased from 8.3 kg in 2000 to 25.3 kg in 2020 and is expected to reach 31.5 kg by 2030 (Habib et al., 2023).

In addition to the accumulation of e-waste, an even more pressing concern lies in the best practices for electronics recycling and disposal. Significant environmental challenges arise from the recycling and disposal practices of e-waste by major global producers (Liu et al., 2019a, b; Kumari and Samadder, 2022; Tansel, 2022). For example, industrialized countries such as the USA, Canada and many EU countries are known for shipping their e-waste to places such as West Africa, India, and China to avoid higher expenses of proper local disposal (Efthymiou et al., 2016; Purchase et al., 2020; Abalansa et al., 2021). In addition, management challenges of locally generated e-waste have been reported

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List of acronyms

BC	British Columbia
CAD	Canadian dollar
EEE	Electronic and Electrical Equipment
EOLE	End-of-Life Electronics
EPR	Extended Producer Responsibility
EPRA	Electronic Product Recycling Association
MB	Manitoba
NB	New Brunswick
NL:	Newfoundland and Labrador
NS	Nova Scotia
ON	Ontario
QC	Quebec
PEI	Prince Edward Island
SK	Saskatchewan

in many developing countries (Nguyen and Lam, 2023; Nguyen et al., 2023). This has created many ethical and equality issues, leading to exacerbation of the global e-waste crisis and endangering both local communities and the planet (Bressanelli et al., 2020; De Vries and Stoll, 2021). Moreover, the challenges of the e-waste collection system include the need for proper recycling techniques to handle hazardous materials and recover valuable metals with appropriate processes (Kumar et al., 2017; Bakhiyi et al., 2018; Romel et al., 2022).

1.1. Electronic waste management in North America

North Americans contributed significantly to e-waste generation, but only a few studies on e-waste management systems have been conducted assessing the current state of e-waste management, proposing recommendations for effective e-waste management systems in North America (Xavier et al., 2021; Rene et al., 2021). Schumacher and Agbemabiese (2019) analyzed the e-waste recycling industry in the United States and found that a centralised program and an increased number of entities have a considerable influence on the e-waste collection rate. Schumacher and Agbemabiese (2019), further suggested that flexible management of e-waste, coupled with annual recycling program goals, constitutes significant factors in the effectiveness of e-waste legislation. Kumar & Holuszko (2016) explored the e-waste management system in Canada and the organizations working on e-waste collection and recycling. Kumar & Holuszko (2016) highlighted provincial variations, noting that Alberta, Saskatchewan, and Yukon lack certain programs present in British Columbia, Manitoba, Ontario, and Quebec.

Additionally, Otto et al. (2018) studied the factors influencing consumers' recycling behavior and the effectiveness of different approaches, such as structural improvements and social enticements. Otto et al. (2018) suggested that environmental motivation and behavioral costs can contribute to an improved e-waste recycling rate. Leclerc & Badami (2023) examined the main drivers and barriers that influence the collaboration of municipalities with an e-waste Extended Producer Responsibility (EPR) program in Quebec, Canada and highlighted the need for transparency and addressing challenges such as the lack of permanent hazardous e-waste collection sites. Habib et al. (2023) concluded that Canada's e-waste recycling infrastructure has yet to develop in line with the electronics development. Several robust management approaches and region-specific waste reduction targets are needed to tackle increasing e-waste, reduce environmental impacts, and increase circular economy potential. Habib et al. (2023) also suggested that governments can intervene in the growing e-waste problem to encourage recyclers by providing more incentives and product designers should consider the economic feasibility of resource recovery from equipment. Kutralam-Muniasamy et al. (2023) examined the effects of citizen involvement initiatives on various end-of-life products in Mexico City and found them overwhelming effective. None of the published studies have specifically considered the effects of stewardship attributes on e-waste management efficiency. Given the rising e-waste and disposal challenges, it is crucial to assess Canada's e-waste management for cost-effectiveness and efficiency thoroughly.

1.2. Electronic Product Recycling Association stewardship program

As one of the fastest-growing e-waste industries in the world, the Canadian Government has taken measures to reduce unsafe disposal of e-waste. E-waste legislation in Canada is set at the provincial level, usually in the form of EPR legislation (Xavier et al., 2021) that handles e-waste through various approaches and programs. Consequently, several organizations are working on collecting and recycling e-waste in Canada, with a collection rate of nearly 20% in 2014, out of which only 15% of e-waste is recycled (Kumar and Holuszko, 2016; Lakhan, 2016). The Electronic Product Recycling Association (EPRA), a non-profit organization, is one of these organizations that focuses on e-waste recycling and reuse by collecting End-of-Life Electronics (EOLE).

EPRA has set the standard for safe electronics recycling - diverting electronics from landfills, preventing illegal exports, and implementing customized recycling solutions. EPRA operates in nine provinces, namely: British Columbia (BC), Saskatchewan (SK), Manitoba (MB), Ontario (ON), Quebec (QC), New Brunswick (NB), Nova Scotia (NS), Newfoundland and Labrador, (NL), and Prince Edward Island (PEI). It manages a network of qualified processors, operators, and drop-off locations. EPRA works with over 7800 e-waste related businesses and over 2100 drop-off locations. Table 1 provides information on the EPRA program structure in different provinces in Canada. EPRA accepts more than 20 significant types of electronic equipment in Canada (Leclerc and Badami, 2020), such as display devices, cellular devices and pagers, non-cellular telephones, home (or personal or vehicle) audio or video systems, computers and computer peripherals, printers, information

Table 1
EPRA program structure in different provinces in Canada.

Province	Responsible Stewards	Regulatory Framework	Performance Goals
BC	Major electronics producers and retailers	EPRA standards and EPRA Stewardship Plan	75% recovery rate, 97% accessibility, 75% consumer awareness (2018)
SK	Manufacturers, retailers, and stakeholders	Waste Electronic Equipment Regulations	90% accessibility, 70% consumer awareness (2018)
MB	Industry-led, not-for-profit association	Industry high standards	Not specified
QC	Producers, distributors, and retailers	EPRA standards and Quebec Product Stewardship Program	65% recovery rate (2011)
NS	Manufacturers, retailers, and stakeholders	Solid Waste-Resource Management Regulations	50% diversion rate (2023)
PEI	Manufacturers, retailers, and stakeholders	Materials Recycling Regulations	Not specified
NB	Industry-led and government-approved program	Clean Environment Act and Designated Materials Regulation	41% recovery rate, 93% accessibility, 70% consumer awareness (2020)
NL	Industry-led and government-approved program	Not specified	95% recovery rate, 94% accessibility, 70% consumer awareness. (2019)

Note: Performance goals are articulated within the approved product stewardship plans of each province.
Data source: (EPRA, 2024)

technology and telecom equipment, musical instruments, battery-powered toys, e-bikes, or e-scooters, and many other electronic devices. EPRA data is systematically collected in different provinces, minimizing data uncertainty. EPRA reports are valuable in quantitative assessment of operational resilience of the Canadian stewardship programs (Hasan et al., 2024).

2. Study objectives, novelty, and contribution

The study objectives are to (i) analyze the e-waste collection trends with respect to e-waste management industry in Canadian provinces from 2013 to 2020 by using EPRA reports, and (ii) evaluate cost-effectiveness in e-waste management with respect to stewardship program expenses in the selected provinces. Unlike other e-waste studies that only discussed EPR program policies and efficiencies in a given state, province, or city, this study comprehensively compares the e-waste management industry characteristics, expenditure, and per capita e-waste collection trends of six Canadian provinces. Some studies suggest that waste business characteristics and expenditures may be important to municipal solid waste recycling rates (Richter et al., 2018; Mensah et al., 2023b). It is hypothesized that operational aspects of stewardship attributes may influence e-waste collection rate. The use of stewardship attributes to evaluate the performance e-waste management system at a regional level is original. By examining the distinctive traits of Canadian provincial stewardship models for e-waste management, a deeper understanding of their impact on the efficiency and effectiveness of e-waste collection processes can be gained (Pan et al., 2019; Bolingbroke et al., 2021; Mensah et al., 2023a). According to Environment Canada, the amount of e-waste generated nationwide is rising by 3–5% yearly (Kumar and Holuszko, 2016), outpacing the recycling rate. This study aims to identify factors affecting e-waste collection rates in Canadian jurisdictions, providing policymakers with insights to address challenges such as awareness, accessibility, and incentives, and enabling them to develop targeted strategies to improve e-waste management and economic circularity.

3. Materials and methods

A total of six provinces were selected in this study, including British Columbia (BC), Saskatchewan (SK), Manitoba (MB), Quebec (QC), Nova Scotia (NS), and Prince Edward Island (PEI). The other three provinces (NL, NB and ON) are excluded in this study due to data unavailability and inconsistencies in reporting periods and waste definitions. The e-waste data for the selected provinces from 2013 to 2020 were collected from EPRA annual reports and the organization's website, with information for 2021 and 2022 currently unavailable. BC was chosen since it is reported that EPRA-BC has delivered best practices in industry-led electronics recycling. According to EPRA reports, SK had the first industry-led electronics recycling stewardship program in North America. MB is in Canadian prairies like SK and is thus chosen for comparison. On the other hand, QC has implemented some unique EPR program regulations. Moreover, NS and PEI are also considered because NS and PEI have more waste management businesses per capita than most Canadian provinces (Richter et al., 2017). The chosen provinces present a diverse array of recycling frameworks, regional contexts, and regulatory approaches, making them suitable for a comparative analysis to inform and improve e-waste recycling practices. Given Canada's geographic vastness, the six selected provinces were categorized into two groups based on their geographical positions (Table 2). Group A encompasses the western provinces of BC, MB, and SK, while Group B comprises the eastern provinces of NS, PEI, and QC. This division explores the program's performance and outcomes when viewing the provinces collectively, and the potential results of resource sharing and collaborative actions among the provinces. Regionalization of waste management system is increasingly popular in Canada (Richter et al., 2021b; Karimi et al., 2022). The adopted groupings will allow better assessment of a regionalized management framework for e-wastes.

There is some discrepancy in the types of products collected by the provinces. For example, BC accepts products such as toys, power tools, and scientific instruments, whereas QC chose not to include household appliances, medical devices, and toys. A total of six indicators are proposed in the current study, including the number of stewards, collection site density, e-waste collected per capita, total local government expenditure, program cost per tonne of e-waste and the amount of e-waste managed per steward. A steward is any active distributor, manufacturer, supplier, or importer of any designated electronic products with provincial EPR. Through EPR, each steward is responsible for the EOLE they sell in the marketplace. Stewards can either take this duty on themselves, or they can delegate it to a third-party producer responsibility organization. In every province, collection site density is equal to the number of collection sites per 10,000 km^2 area of the respective province. Moreover, the amount of e-waste managed per steward is equal to total e-waste collected in tonnes divided by total number of stewards. All monetary inputs such as program operating expenditures and program cost per tonne of e-waste are expressed in Canadian dollars (CAD).

The relationships of the parameters are analyzed by using linear regression. In the environmental and waste management areas, regression analysis is frequently used to identify trends and connections between two variables (Liu et al., 2019a, b; Tian et al., 2022) due to its simplicity and interpretability. R-squared is a measure of how well the independent variables explain the variability in the dependent variable within the linear regression model. The finesses of the linear regression model are defined like (Richter et al., 2017) as follows: linear relationship not detected ($0 \leq R^2 \leq 0.2$), weakly fit ($0.2 \leq R^2 \leq 0.5$), moderately fit ($0.5 \leq R^2 \leq 0.8$), and reasonably fit ($R^2 > 0.8$).

4. Results and discussion

4.1. Analysis of E-Waste collection and business characteristics in Canada

Fig. 1 illustrates variations in e-waste collection rates across Canadian provinces. Notably, BC, NS, and PEI lead with the highest average rates, at 4.1, 4.1, and 3.9 kg/capita, respectively. This phenomenon can be attributed to effective government regulations to reduce e-waste

Table 2
E-Waste management metrics in Canadian provinces in 2020.

Group	Province	Business Size	Collection sites	Public Awareness (%)	Program Accessibility (%)
A (Western)	BC	1791	292	72	99
	MB	576	97	80	96
	SK	782	100	87	93
B (Eastern)	NS	649	78	94	99
	PEI	372	12	87	100
	QC	1787	979	76	99

Note: Program accessibility is measured by the percentage of the population within specified driving distance (45 min in rural or 30 min in urban areas) of an EPRA Drop-off Centre. Public awareness is defined by the percentage of the population that is knowledgeable about EOLE recycling methods (EPRA, 2024).
Data source: EPRA 2024.

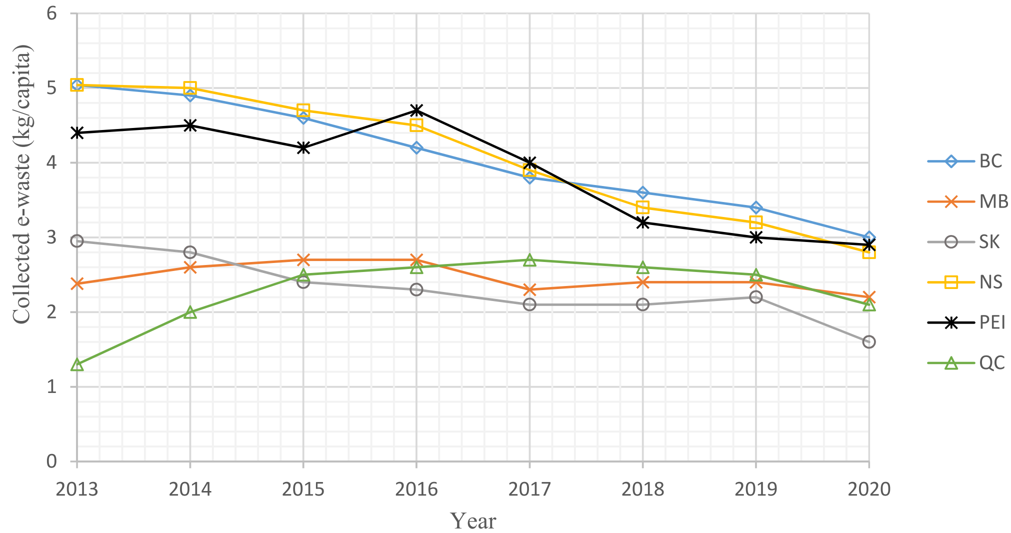
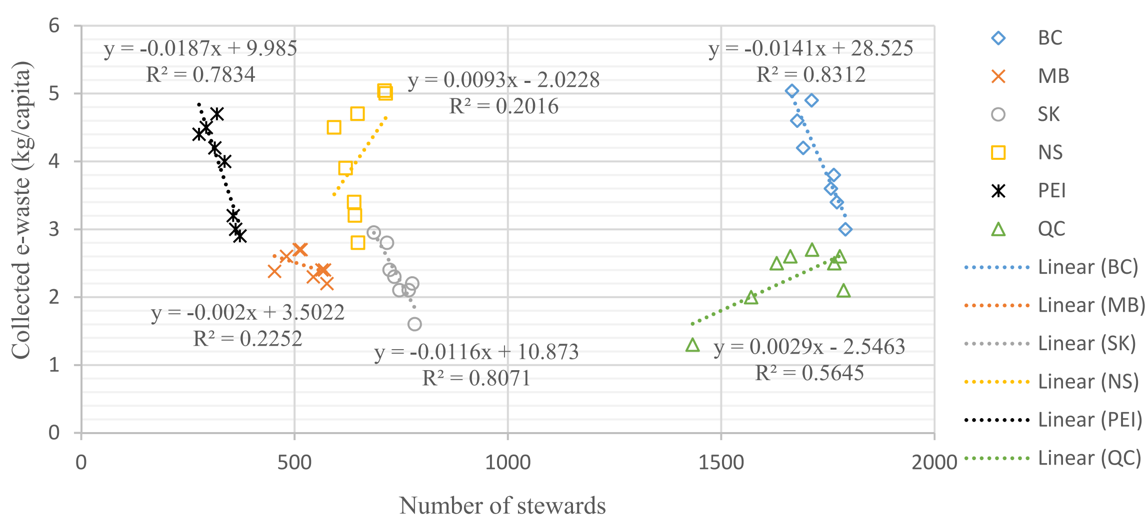
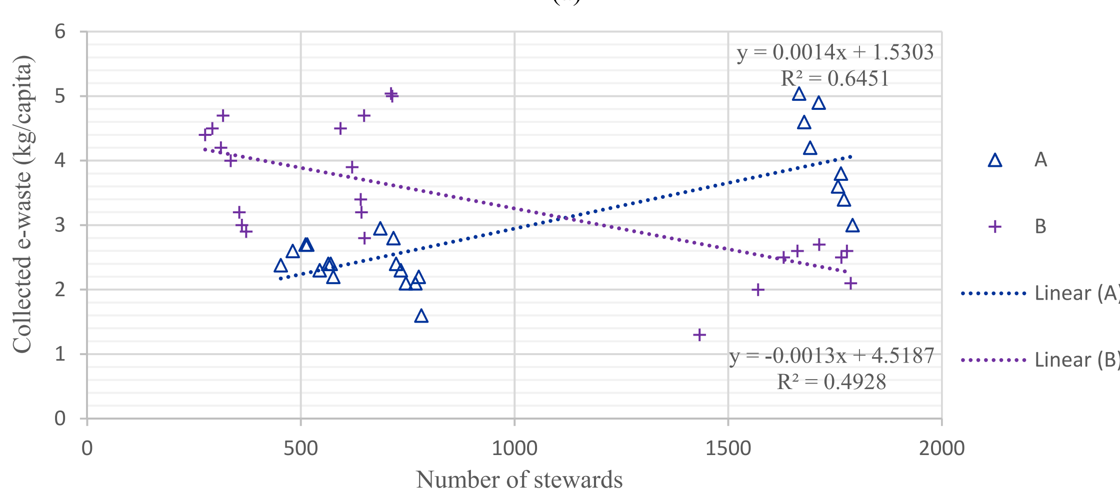


Fig. 1. Temporal changes in collected e-waste (kg/capita) from 2013 to 2020.



(a)



(b)

Fig. 2. Relationship between per capita e-waste collected and number of stewards from 2013 to 2020 (a) within provinces (b) in Western and Eastern Canada.

landfilling (Kumar and Holuszko, 2016) and the adoption of designing for the environment principles in e-waste management (Nguyen et al., 2019). Compared to BC and NS, the PEI rates were less consistent temporally, probably due to a smaller population and thus the residents behaviors are more sensitive to policy changes. The collection rates at MB, SK, and QC were consistently less than 3.0 kg/cap. QC initially had the lowest collection rate at 1.3 kg/capita in 2013, increasing to 2.1 kg/capita in 2020 due to government initiatives promoting e-waste disposal. MB and SK exhibit lower e-waste collection rates, possibly influenced by higher rural populations and limited collection accessibility (Assuah and Sinclair, 2021; Ghosh and Ng, 2021; Richter et al., 2021a). According to EPRA annual reports, the average collection accessibility was 91.9% in MB and 92.9% in SK during the study period, which was lower than the other four provinces.

During the study period, a declining trend (slope ranges from −0.16 to −0.35) in e-waste collection rates is evident in most provinces except QC. An overall decreasing trends are attributable to technological advancements favoring smaller and more efficient devices, lack of awareness and training for safe handling and processing of materials (Habib et al., 2023). Additionally, in Canada the primary contributors of e-waste are computers, televisions, cell phones, lamps, and lighting products (especially light emitting diodes) and miniaturization of these devices has led to a decrease in the overall collected weight of e-waste (Kumar and Holuszko, 2016). For example, wireless mobile applications and power amplifier duplexers continue to shrink in size (Lakhan, 2016). Besides sending unwanted electronics to drop-off centers, some Canadian households are trading electronics with retailers, keeping them in storage, or giving them away, which is also contributing to the decline in e-waste collection rates. The composition of the e-waste stream also plays a role, with large household appliances (such as refrigerators, washing machines, treadmills, and other large electronic devices) dominating by weight but less bulky items (such as cellphones, toys, and laptops) prevailing in quantity (Habib et al., 2023). Similarly, the e-waste collection rate in North America has decreased due to the disappearance of bulky CRT televisions and monitors (Althaf et al., 2021). The decline in total e-waste mass indicates the need for a shift in e-waste regulations, from a focus on e-waste mass to both the count and type of devices. It is recommended to enhance public education and drop-off centers accessibility and set achievable EPR program goals to improve e-waste collection rates in Canadian provinces.

Fig. 2a shows the relationships between collected e-waste and the number of stewards for different Canadian provinces. Only NS (yellow squares) and QC (green triangles) show positive correlation between collected e-waste and number of stewards. Historical records show that the number of stewards increased in all provinces during the study period, except NS, which experienced an 8.72% reduction from 711 stewards in 2013 to 649 in 2020. The amount of collected e-waste in NS also declined by 44.44% during the study period, resulting in a positive slope (+0.0093) with an R^2 of 0.2 (Fig. 2a). NS generally has a well-established waste management program (Richter et al. 2018, 2021b), the regression results suggest that it may be difficult to sustain an effective e-waste stewardship program. A positive slope (+0.0029) is observed in QC (green triangles) due to a 24.7% increase in the number of businesses and a substantial 61.5% increase in collected e-waste during the study period. QC has adopted more harmonized EPR programs and implemented regulatory measures, including enforcement mechanisms, penalties for non-compliance, fee modulation, enforcement of the 3R hierarchy, and local processing, surpassing other Canadian provinces (Leclerc and Badami, 2020).

The regression analysis for BC, MB, SK, and PEI reveals a negative relationship, with R^2 ranging from 0.23 to 0.83 which indicates that e-waste collection rate is not sensitive to increased number of e-waste businesses in these provinces. It appears that the number of stewards may not be the dominating factor on e-waste recycling in Canada. BC has a negative slope (−0.014) and R^2 of 0.83, likely stemming from a 40.5% reduction in collected e-waste and declining percentages of public awareness. According to EPRA reports, in BC, 80% of the population was aware of proper recycling of e-waste in 2014, which then declined by 8% at the end of the study period in 2020 (Table 2). Such a decline in awareness is crucial to understanding the dynamics of the stewardship model's success, as highlighted by Gollakota et al. (2020). The findings suggest that (i) harmonized EPR programs in QC, (ii) participation by stewards in NS, and (iii) consumer awareness in BC affect their e-waste collection rates. Thus, it is crucial to foster collaboration among various stakeholders, launch innovative public awareness campaigns, and establish robust monitoring and evaluation mechanisms to ensure the success of an e-waste management program.

The e-waste recycling behaviors appear sensitive to the geospatial location. In Fig. 2b, while considering the Western province (BC, SK, and MB) together as Group-A, a positive slope of +0.0014 ($R^2 = 0.65$) indicates that there's a tendency for a rise in collected e-waste per capita to be associated with an increase in the number of stewards. The positive correlation in Group A could be due to aggressive performance targets set by most of the provinces in this group (Table 1). The presence of over 20 processors in BC, 10 in MB, and 10 in SK, as highlighted by the EPRA website, suggests a robust infrastructure contributing to increased demand and supply for e-waste services. This implies that the collaborative efforts or combined resources of the provinces may result in a more effective e-waste management system when viewed as a whole, potentially overcoming the negative trends observed at the individual provincial levels. Ilankoon et al. (2018) also suggested that collaborative efforts in uniting regions may be important to the successful implementation of comprehensive e-waste management strategies. On the other hand, the observed negative correlation (slope −0.0013) in Eastern Canada (Group B) can be attributed to the limited number of e-waste processors in PEI & NS and the exclusion of e-waste from its curbside collection program in NS. Differences in government support levels, and socio-economic factors on recycling behavior may further hinder efficient collection (Parajuly et al., 2020; Yadav et al., 2022) despite strong business participation. Eastern Canada already achieved reasonable e-waste collection rates during the study period (Fig. 1), and the sole addition of more stewards may be less effective. Addressing these limitations is crucial for efficient e-waste management. The findings prompt consideration of stewardship model characteristics that emphasize collaboration, common goals, and shared resources as essential components for success.

The land area of the provinces considered in this study are not consistent, and collection site density is computed. Fig. 3a shows a negative correlation between collected e-waste per capita and collection site density, except for QC. A positive slope (+0.36) with a strong fit relationship (shown in green, $R^2 = 0.80$, $P < 0.005$) is observed in QC. The result may be due to the higher number of collection sites compared to other jurisdictions. QC, being the second most populous province, increased the total number of collection sites by 95.8% (from 500 to 979). Other potential reason might be different recycling regulations, as QC producers were required to gradually comply with the minimum recovery rate of 65% (Leclerc and Badami, 2020).

In contrast, the BC, SK, and PEI regression models are similar, with a negative slope (from −0.0067 to −2.96) and R^2 values ranging from 0.79 to 0.87. The observed negative correlation is interesting, it highlights the importance of considering factors beyond the increased number of collection sites at provincial level. According to Shi et al. (2023), consumers' response towards the disposal of EOLE is significantly influenced by accessibility to collection sites. The availability of collection sites has been identified as a significant predictor of e-waste recycling behavior in China (Wang et al., 2016). Thus, several factors such as consumer behavior, inefficient management systems and frequency of drop-off facilities affect the collection rate of e-waste (Schumacher and Agbemabiese, 2021). Therefore, it becomes imperative to increase the number of collection sites, optimize their distribution, ensure accessibility, enhance opening hours and drop-off flexibility, and address regional variations for more effective e-waste management.

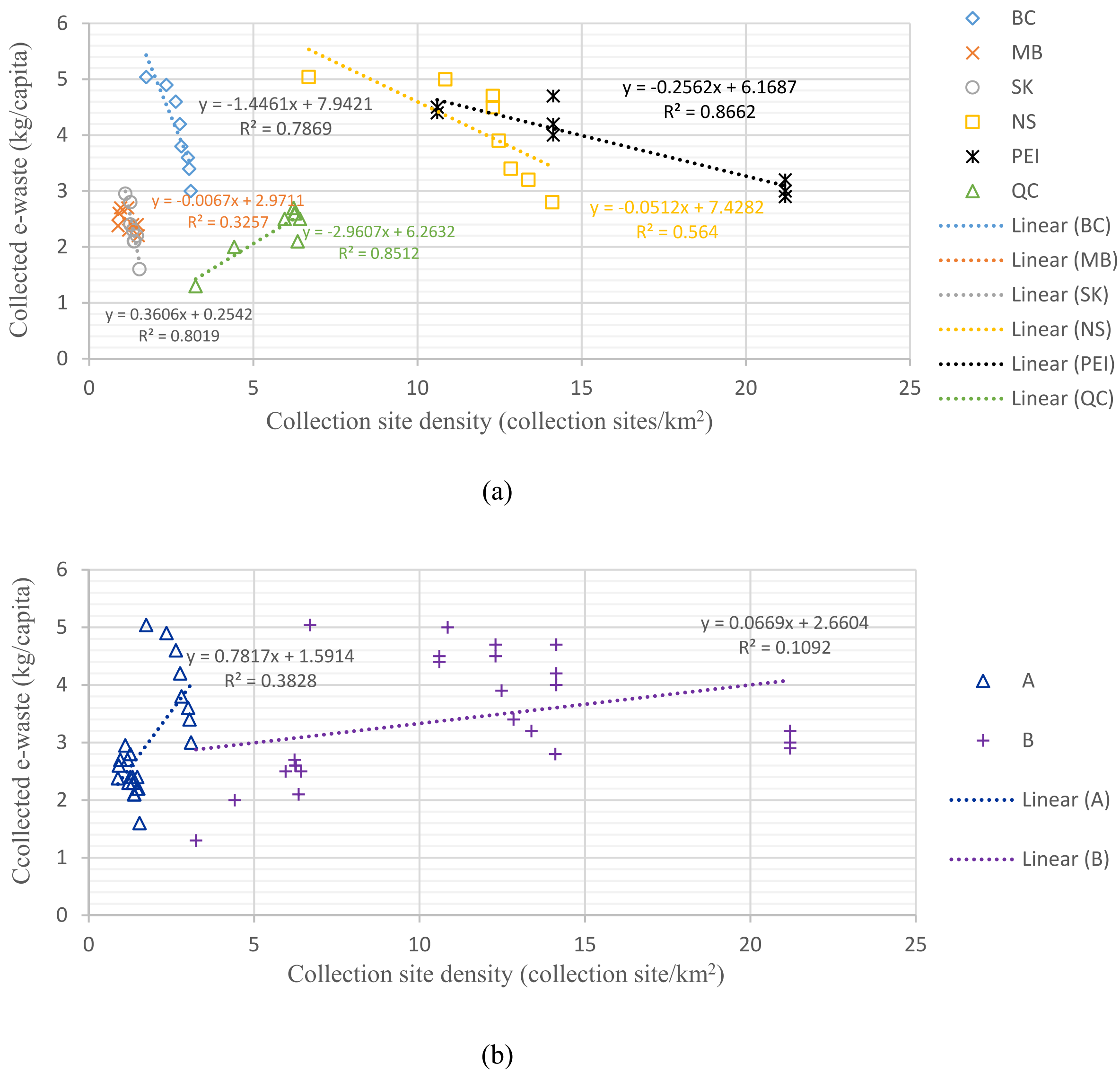


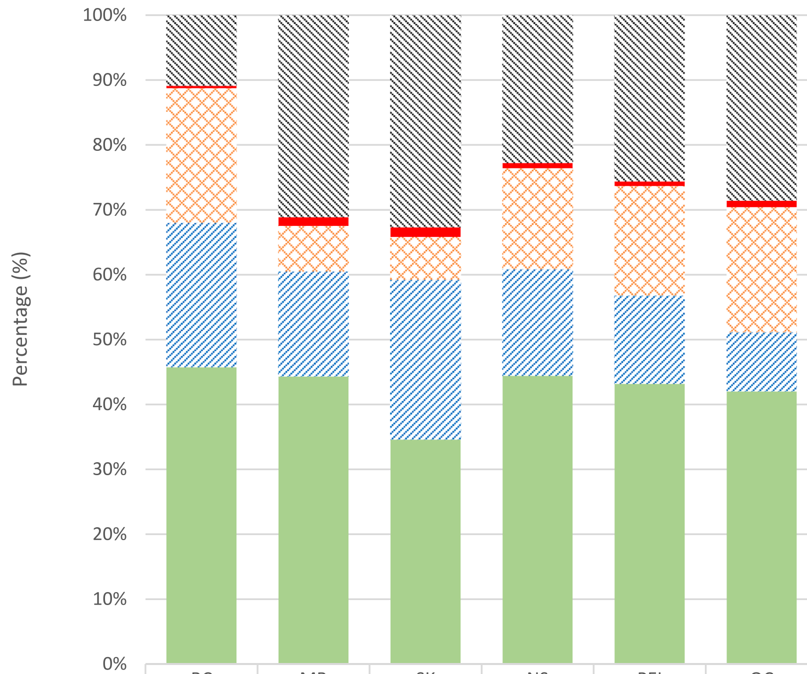
Fig. 3. Relationship between per capita e-waste collected and collection site density (a) within provinces (b) in Western and Eastern Canada.

Regression results using regional data show weak, but positively correlated, relationships. In Fig. 3b, the regression analysis for both Western Canada (Group A, blue triangles, slope +0.78) and Eastern Canada (Group B, slope +0.067) shows a positive trend, with weak R^2 values for both groups (0.38 & 0.11). This could suggest that a coordinated approach to waste management, involving multiple provinces, might be more effective in enhancing e-waste collection, possibly through shared resources or collaborative policies. Regionalized approach in Canadian waste management can be more cost-effective, especially for border cities (Ghosh and Ng, 2021; Ghosh et al., 2023). Enhancing accessibility through integrated collection sites with other waste management systems, like curbside pickup and municipal facilities, could further contribute to improved e-waste collection rates (Bouvier and Wagner, 2011). Strategic placement of these sites and regional coordination are essential (Sagnak et al., 2021; Yuan et al., 2022), highlighting the importance of integrated systems to maximize the effectiveness of e-waste management models across diverse contexts.

4.2. Expenditure in the e-waste sector

Fig. 4 shows the average distribution of expenditure in direct operations related to e-waste during the study period. In all cases, majority the budget was spent on the processing of e-waste. BC spent 45.7 % (CAD 9.0 million/year) of total annual expenditure (CAD 19.7 million/year) on processing. NS and PEI also spend about the same percentage as BC, accounting for 44.5 % and 43.2 %, respectively. Given that NS and PEI have nearly the same average e-waste collection rate as BC (Fig. 1), significantly less consumer awareness (CA) and administration cost were spent in BC at CAD 2.1 million/year.

Though SK has the second lowest e-waste collection rate, it spent an average of 24.6 % on the collection of e-waste, the highest among the provinces. The optimization of the waste management system requires a different approach in SK (Otto et al., 2018), which contributes to the higher spending on the collection of e-waste. More effort is needed to improve the e-waste collection program in SK. On the other hand, QC spent the lowest amount of the annual budget (19.2%) on collection, probably to establish permanent locations for collecting hazardous e-waste in some municipalities as some were at risk due to lack of proper facilities (Leclerc and Badami, 2023). MB and SK spent the lowest percentage on waste transfer and storage, 7.0% and 6.6% respectively. Transportation costs for other waste, such as municipal solid waste, are also less in SK compared to other provinces (Mensah et al., 2023b). In the Consumer awareness and administration category, SK spent 32.7% of the annual budget (about CAD 1.1 million/year), probably due to SK



	BC	MB	SK	NS	PEI	QC
CA* & administration (x 1,000)	2,135	1,061	1,172	974	161	5,863
QA* & recycler audit (x 1,000)	82	45	54	35	5	204
Transportation & storage (x 1,000)	4,074	238	238	666	106	3,945
Collection (x 1,000)	4,392	552	882	701	86	1,876
Processing (x 1,000)	9,005	1,509	1,241	1,902	272	8,611

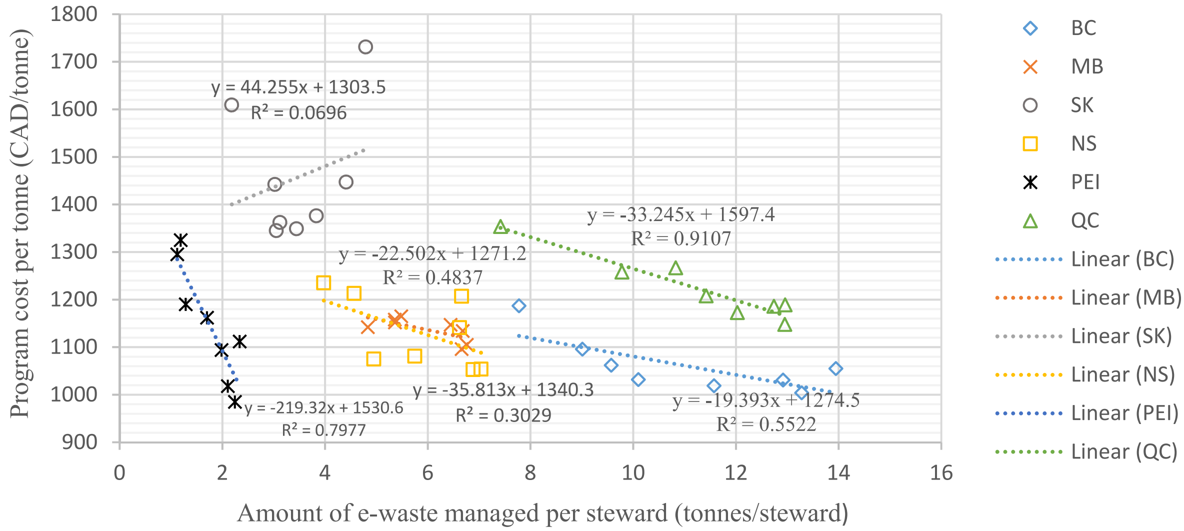
Note: QA*= Quality assurance, CA*= Consumer awareness

Fig. 4. Total annual local government expenditure from 2013 to 2020
Note: QA* = Quality assurance, CA* = Consumer awareness.

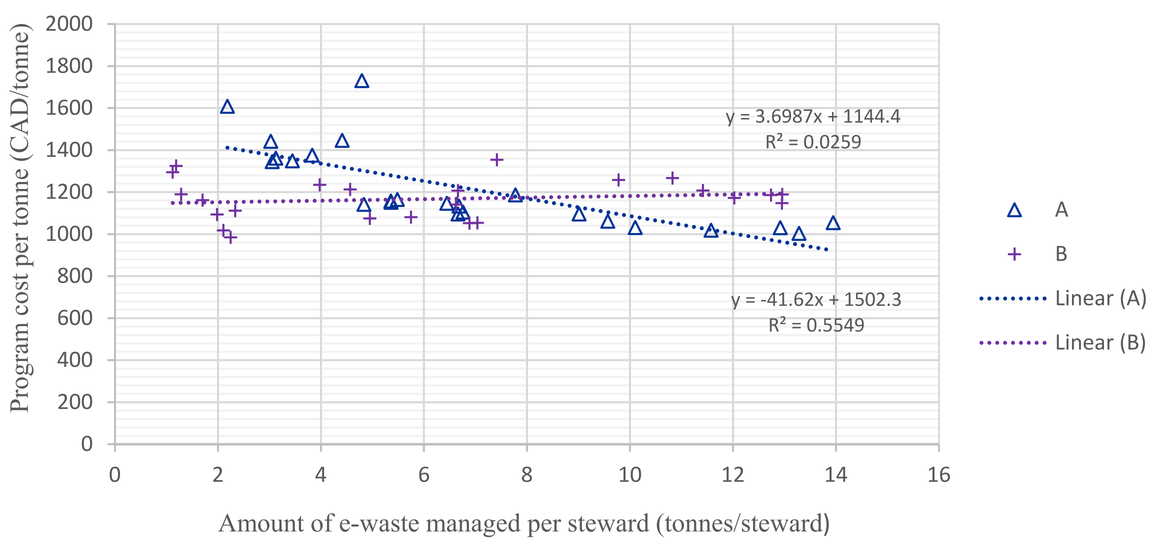
giving more importance to public awareness. Thus, SK had the highest percentage (87% in 2020) of the population aware of the EPRA program in the Eastern Canada (Table 2). According to the EPRA annual report, SK's marketing efforts were dedicated to the dual branding of the Saskatchewan Waste Electronic Equipment Program and EPRA, contributing to the expenses. Similarly, after SK, MB and QC spent about 31.2% and 28.6%, respectively, on this operation. Consequently, in 2013, MB and QC had low public awareness rates of 55% and 52%, respectively, and dramatically rose to 80% and 76% by 2020 (Table 2). Unlike others, BC spends only 10.8% on this category, the lowest among the province. These variations in expenditure highlight the importance of tailoring stewardship models to optimize resource allocation in different regions. A cost-effective approach should integrate region-specific considerations, striking a balance between collection, processing, and consumer awareness.

Not only the distribution of expenditures are inconsistent among the provinces, the management cost per tonne is also not the same for all provinces. The program cost was generally CAD1,000–1730/tonne. In Fig. 5a, program cost per tonne correlates negatively with the amount of e-waste managed per steward for all provinces except SK. The regression line of SK has the lowest R^2 of 0.07, probably due to the amount of e-waste managed per steward halving during the study period. The amount of e-waste managed per steward ranged from 2.2 tonnes/steward to 4.8 tonnes/steward, with an average of CAD 1457.6/tonne program cost. Moreover, SK has the highest number of landfills per capita among the provinces, as well as a skewed spatial population distribution, making waste management systems more challenging (Richter et al., 2021a; Ghosh et al., 2023), resulting in high e-waste handling costs. PEI shows a moderate R^2 of 0.79 and a negative slope (−219.32) because the program cost per tonne of e-waste increased by 16.5 % during the study period, with the lowest average tonnes of e-waste managed per steward (1.7 tonnes/steward). QC has a negative correlation (Slope −33.25, $R^2 = 0.94$), with amount of e-waste managed per steward ranging from 7.4 tonnes/steward to 9.8 tonnes/steward with an average program cost per tonne of CAD 1222.88/tonne. It indicates that as businesses manage larger volumes of e-waste, overall expenditure on e-waste recycling can be done more cost-effectively. As the amount of waste managed increases, EPRA and recycling businesses can benefit from lower costs per tonne due to operational efficiencies and the ability to spread fixed costs over a larger volume of waste (Shaikh et al., 2020).

In the regional analysis (Fig. 5b), the negative correlation (slope of −41.62, $R^2 = 0.55$) and in Western Canada (Group A) also indicate cost efficiencies when managing larger quantities of e-waste per business. Stewards in Western Canada handled 2.2–14.0 tonnes of e-waste, with program cost ranging from CAD1,000–1730/tonne. The findings reveal nuanced relationships between program cost, e-waste management efficiency, and economies of scale. Due to the nature of the materials, e-waste recycling is expensive due to its high costs and relatively low yields (Ilankoon et al., 2018). However, the findings of this study suggest that the shared recycling infrastructure among provinces has the potential to enhance collection efficiency. Policymakers, businesses, and stakeholders can use these insights to develop strategies that enhance e-waste recycling programs and reduce costs associated with waste management. The correlation in the Eastern Canada (Group B) was weak ($R^2 = 0.02$), indicating a lack of consistent cross-jurisdictional system efficiencies. It appears that the recycling behaviors of the residents were quite different among the provinces. A diverse range of e-waste managed per steward was observed (1.1–13.9 tonnes/steward), probably due to the difference in acceptable recyclables and program strategies. It is imperative to design location-specific e-waste collection



(a)



(b)

Fig. 5. Correlation between program cost per tonne and amount of e-waste managed per steward from 2013 to 2020 (a) in individual provinces (b) in group A & B.

programs that minimize disparities in acceptable electronic products and encourage collaborative e-waste management initiatives, streamlining recycling efforts.

5. Limitations

In this study, all e-waste was quantified by weight and thus sensitive to the fraction of bulky items (e.g. household appliances). However, not all provinces include large household appliances in their EPR programs for e-waste, skewing the national data set. Uncertainties in Canadian waste data are not uncommon and have been reported previously (Bruce et al., 2016; Wang et al., 2016; Chowdhury et al., 2017). In this study, only e-waste collected by EPRA drop-off locations is considered. Small amounts of special e-waste may be handled directly by the provincial stewards and are excluded. E-waste that is not recycled and permanently disposed at landfill is omitted.

The effectiveness of stewardship programs depends mostly on residents' support and regulations (Kutralam-Muniasamy et al., 2023; Wang and Huo, 2023). Generally, the longer a program has operated, the more effective it is due to the increased awareness. Not all e-waste management stakeholders were considered in this study. Other stakeholders such as decision makers of private entities (Hashmi et al., 2023) and governmental bodies (Xie et al., 2024) may be important to improve environmental sustainability of the e-waste management model. A more comprehensive list of acceptable EOLE might also yield a higher collection rate. However, both factors were not explicitly considered in the provincial-wide analysis due to the frequent use of staged project implementation over time and pilot projects for specific e-waste in Canada.

6. Conclusion

This study revealed significant insights into the e-waste collection and management trends across various Canadian provinces. Despite starting lower than BC, NS, and PEI, e-waste collection rates per capita in QC's e-waste collection rates per capita showed an impressive increase of more than 1.5 times between 2013 and 2020. This growth underscores the effectiveness of QC's program strategy, contrasting with the declining collection rates observed in the other five provinces, raising concerns about the effectiveness of their outreach and collection efforts. BC has a negative slope of −0.014 due to only 7.5% increase in number of stewards, while the percentage of public awareness declined by 8%. QC's positive slope of +0.0029 resulted from a 24.7% rise in the number of stewards driven by harmonized EPR programs. QC's proactive approach extended to a 95.8% increase in collection sites, resulting in a notable 61.5% surge in e-waste collection rates, aligning with the province's commitment to meeting recovery rate targets. Interestingly, positive correlations (slopes ranging from 0.07 to 0.78) between e-waste collection rates and collection site density were noted in groups A and B. The positive correlations in the grouped analysis of stewards and collection site density (slope of 0.0014 and 0.78, respectively), especially for Group A (western Canadian provinces), suggest that a coordinated approach to waste management through shared resources or collaborative policies may have a positive impact on e-waste collection rates.

SK and MB demonstrated room for improvement, allocating relatively lower percentages (6.6% and 7.0%, respectively) of their budget to e-waste transfer and storage. BC's allocation of only 10.8% to public awareness campaigns indicated an area where necessary measures could boost e-waste collection rates. QC has managed e-waste, ranging from 7.4 to 9.8 tonnes/steward, with an average program cost per tonne of CAD1,222.88/tonne. The program cost per tonne of e-waste tends to be lower when Canadian stewards handle more waste. It suggests that, when businesses process larger volumes of e-waste, recycling costs decrease. Given the sparse population distribution of Canada, it may be difficult to take advantage of the economy of scale.

Stewardship model attributes emerge as crucial factors in increasing e-waste collection rates, with program strategies and budget allocations playing pivotal roles. The study suggests that a coordinated and proactive approach, along with effective resource allocation, can positively impact e-waste management outcomes. Policymakers globally can draw insights from these findings to develop more efficient e-waste collection systems on a larger scale. However, more research is needed for region-specific strategies and e-waste collection systems, which has received very little attention. Future research should explore diverse e-waste categories on recycling efficiency and consider the influence of product design on stewardship program performance. Moreover, the potential benefits of regionalization of waste management systems and establishment of a national e-waste legislation should be thoroughly examined.

CRediT authorship contribution statement

Anica Tasnim: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Rumpa Chowdhury:** Writing – review & editing, Validation. **Sharmin Jahan Mim:** Writing – review & editing, Validation. **Kelvin Tsun Wai Ng:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Hillary Adu-Darko:** Writing – review & editing.

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

Data will be made available on request.

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