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Integrating traditional ecological knowledge into a circular economy framework using the example of consumer durable goods for northern rural communities

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Consumer Durable Goods (CDG)s have a large energy and water footprint during their lifecycle and are one of the largest contributors to municipal waste upon disposal. While CDG waste becomes invisible to consumers in urban communities, due to relatively well-established waste management infrastructure, it is inequitable in rural communities where deteriorating/decomposing goods remain on native lands/landfills and pose a risk to people and ecosystems. Therefore, a sustainable approach that emphasizes resource efficiency, waste reduction and an inclusive framework for the design, use and circularity of CDGs is imperative. This study examines the circular economy (CE) as a promising approach for CDGs in the Canadian context, where there are unique geographical challenges, particularly in remote, rural, and indigenous communities with limited recycling and repair infrastructure. It carefully considers the integration of Traditional Ecological Knowledge (TEK) in developing sustainable strategies for the circular materials management of CDGs to mitigate these challenges. This critical analysis explores global and national consumption trends and translates them into local knowledge gaps to reveal the barriers to the effective adoption of CE practices and identifies the opportunities and challenges in integrating TEK into CE for CDGs in remote and rural communities. It also provides recommendations and insights into how CE principles infused with TEK and indigenous wisdom can address UN SDGs 10, 11, 12, 13, 14, 15 and 3 globally and help build capacity to support local solutions for waste reduction, resource efficiency, improved community economy and environmental health of remote and rural communities.

Sustainability spotlight

Waste from consumer durable goods (CDGs) not only contributes significantly to municipal waste and environmental burden but it is particularly inequitable for northern remote and rural communities that have insufficient repair and recycling infrastructure. An inclusive Circular Economy (CE) framework for the design, use, and end-of-life management of CDGs that integrates Traditional Ecological knowledge (TEK) is proposed, to promote resource efficiency and waste reduction in these communities. The proposed framework aligns with UN SDGs 10 (Reduced Inequalities), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), 14 (Life Below Water), 15 (Life on Land), and 3 (Good Health and Well-being), offering a holistic solution to improve environmental health, and social equity.

1. Introduction

According to the US Census Bureau,[1] consumer spending is the largest driver of the economy, contributing billions of dollars to the world economy with significant power to directly impact jobs and tax revenue. The six-year annual revenue trends for the Organization of Economic Cooperation and Development (OECD) consumer expenditure and emerging economies such as China and India in Asia show that consumer expenditure is consistently growing globally (Table 1).[2] Table 2 includes Canada's household final consumption expenditure data. Personal expenditure on durable goods includes house trailers, new and used automobiles, furniture, household appliances, radio and television sets and sporting and wheeled goods. These data provide a clearer understanding of spending trends within Canadian communities, complementing the global context presented in Table 1.

Durable goods are products that have a lifetime of more than three years as defined by the US Environmental Protection Agency (EPA).[4] Consumer durable goods (CDGs) (such as refrigerators, televisions, washing machines, vacuum cleaners,

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Table 1 Growth trend in annual revenue from consumer expenditure for consumer durable goods in OECD and emerging economies (India and China)

	Revenue from consumer durable goods (USD, in billions)[a]					
Countries	2017	2018	2019	2020	2021	2022
OECD	2441	2540	2605	2658	3104	3456
India	38	43	41	41	52	59
China	525	564	598	592	674	698

[a] Fixed 2022 exchange rates.

Table 2 Household final consumption expenditure

Chained (2017) dollars (in billion Canadian dollars)						
Country	2017	2018	2019	2020	2021	2022
Canada Source[3]	644.11	662.14	663.17	613.62	673.15	674.27

etc.) constitute a large part of consumer expenditure worldwide. The CDGs market is a major driving force in the economy, and businesses benefit from increased in manufacturing, transportation, sales, profits and taxes when consumers spend more.[5] These include large and small appliances, furniture/furnishings, rubber tires, lead–acid batteries, electronics and miscellaneous durable goods such as luggage, sporting goods and household goods. For long lasting function and durability, CDGs are made from materials including wood, metals, plastics, glass, paper and paperboard, rubber, leather and other miscellaneous inorganic and organic wastes.[6] The US EPA and the solid waste diversion report by the Canadian government measure the generation, recycling, composting, combustion, energy recovery and landfilling of these materials from the durable goods in municipal solid waste (MSW).[7] The data from these measurements indicate that the waste management of these goods and materials requires strategic sustainable materials management, planning and reporting.[7,8] Table 3 shows the categories of CDGs and their associated generation, landfilling and recycling as characterized in 2018 by the US EPA.

In 2018, in the US and Canada, 57 and 36 million tons of MSW were generated, with waste from CDGs contributing 20% and 36% of the overall MSW, respectively.[4,9]

All member states of the United Nations (UN) adopted the 2030 Agenda for Sustainable Development in 2015, providing a blueprint for peace and prosperity for people and the planet, both now and in the future. The 17 Sustainable Development Goals (SDGs) are at the heart of the agenda. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth, while tackling climate change and working to preserve our oceans and forests.[10] From Table 3 it is evident that large appliances have a large generation and landfilling footprint and are also dependent on energy resources for their use without contributing to energy recovery through combustion. These have direct implications for the UN SDGs 12 (Responsible Consumption and Production), 7 (Clean and Affordable Energy) and 13 (Climate Action), providing opportunities to redesign renewable energy CDGs with an equitable, circular, regenerative model keeping both rural and urban communities in mind.

Preventing and diverting waste by reusing, repairing, refurbishing, remanufacturing, repurposing, recycling and composting is a key component of a more circular economy which can help reduce the impact of solid waste on the environment.[7] In Canada, although the diversion rate of MSW from landfills has increased consistently since 2002, the province of Newfoundland and Labrador (NL) showed the lowest diversion rate at 10%,[9] compared to Ontario and Quebec which had the highest diversion rates at 25% and 33% respectively.[9] Although this seemingly appears to be a failure of consumer behavior and waste management, it requires a deeper insight into population demographics, geographical location and a systemic understanding of the rural *versus* urban waste management criteria as well as the inequities associated with waste management in northern rural communities that result in these statistics. These statistics impel a more circular, equitable and proactive approach to the design of materials used in manufacturing CDGs, especially for achieving an inclusive net-zero transition by 2050.

Due to increasing affordability, the CDGs have become more accessible to consumers, which has resulted in an increase in demand and manufacture (Table 1).[1] With the growing influence of the CDGs industries on the economy, this sector significantly influences businesses, policymakers, and societies in general. Therefore, understanding the drivers and trends of the CDGs sector along with its resource, environmental and health impacts along the product life cycle is critical.[5] The Ellen MacArthur technical cycle is particularly useful in understanding how CDGs can be maintained, repaired, reused, refurbished, remanufactured, and ultimately recycled within the technical cycle of the CE (Fig. 1). This model emphasizes extending product life through repair, refurbishment, and second-hand markets before final recycling.[11]

The inner circle shows the power of CE to keep products, materials, and resources circulating within a local system through repair, reuse, and remanufacturing to minimize resource extraction and waste. This principle is especially relevant to rural and indigenous communities, wherein TEK has encouraged resource conservation, localized repair economies, and sustainable craftsmanship.[12,13] Studies have shown that indigenous circular practices resonate with closed-loop systems, reducing dependency on external supply chains.[14] In rural settings, community connections enable the sharing, repairing, and refurbishing of durable goods in line with inner-circle waste minimization and value preservation principles.[15] These practices contrast with conventional linear economic models and highlight the sustainability benefits of localized circular systems. Enhancing policy support for CE transitions in rural and indigenous regions will require scaling up local repair economies, revitalizing traditional craftsmanship, and integrating TEK-based models into mainstream circular economy

Table 3 Consumer durable goods categories and their waste management data

CDG Category	Example items	Recovered items	Generated (million tons)	Recycled (million tons, %)	Landfilled (million tons, %)	Comments
Major appliances	Refrigerators, washing machines, and water heaters	Ferrous metals, plastics	5.3	3.1 (58%)	2.1 (40%)	Not accepted for combustion or composting with energy recovery
Small appliances	Toasters, hair dryers, and electric coffee pots	Not provided	2.2	0.12 (5.6%)	1.6 (75.9%)	To recover energy, insignificant number of small appliances were combusted (18.5%)
Furniture & furnishings	Sofas, tables, chairs, and mattresses	Potential unmeasured recovery of wood, textiles and metals	12.1	0.04 (0.3%)	9.7 (80%)	To recover energy, significant number of furniture was combusted (19.5%)
Carpets & rugs	Carpets	Carpet fiber, backing and padding	3.4	0.31 (9.2%)	2.48 (73%)	To recover energy, slightly larger number of carpets and rugs were combusted (17.8%)
Vehicle tires	Only included are tires from passenger cars, trucks and motorcycles	Rubber, steel, fiber and nylon	6.5	2.61 (40%)	1.2 (18.5%)	Tires used in large equipment, aviation or industrial applications are not included Tires recovered for fuel are not included Tires going to combustion facilities as fuel are included in the combustion estimates
Lead–acid batteries	Lead–acid batteries from automobiles, trucks and motorcycles	Some electrolytes and other materials in batteries from solid waste, along with recovered lead and polypropylene	2.9	2.87 (99%)	<1%	Lead–acid batteries are not accepted at combustion facilities
Consumer electronics	Computers, TV, video cameras, DVDs, VCRs, and stereo systems	Not provided	2.7	1.04 (38.5%)	N/A	EPA does not currently have information on the amount of selected consumer electronics that are sent to landfills. These products are included in total miscellaneous durables
Total miscellaneous durable goods	Consumer electronics such as television sets, videocassette recorders, personal computers, luggage and sporting equipment	Ferrous metals, as well as plastics, glass, rubber, wood and other metals	24.8	1.5 (6%)	20 (81%)	—

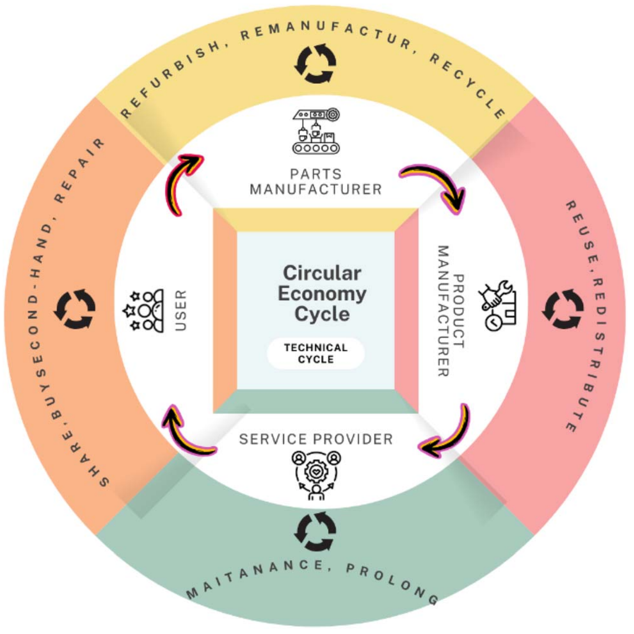

Fig. 1 The circular economy product technical cycle.

strategies.[16] Strengthening these practices aligns with global CE goals while respecting indigenous self-sufficiency and sustainability principles.

The product life cycle of CDGs (Fig. 2) includes (i) the beginning-of-life stage that includes both the design and production stages, (ii) the middle-of-life stage which includes the use and second life stages and (iii) the end-of-life stage that includes disposal.

The current design of CDGs in the beginning-of-life phase and market strategies that maximize profitable production and sales in the use phase, accompanied by planned obsolescence just beyond the mandated three years that denies a second product life, are becoming common.[1] The latter further encourages modular designs in the beginning of life that prevents convenient repair to promote purchase of new products made from virgin materials.[11] These stratagems have led to an intentionally reduced product shelf life to increase sales of newer products without any extended producer responsibility (EPR).[5] Without any known mandate requiring discarded products to be returned to producers, all disposed products ultimately end up in landfills at the end-of-life stage (UN SDG 12) causing severe ecological damage.[17] These have amplified impacts on traditional food sources (UN SDG 3) that become contaminated with leached metal and plastic additive pollutants emerging from the disposed CDGs, leading to adverse effects on local ecosystems including water, soil and air (UN SDGs 14, 15 and 13). Ultimately, these impacts are biomagnified to species and humans living in the surrounding areas where vulnerable populations in the remote and rural communities (UN SDG 10 and 11) without access to advanced waste management systems are most inequitably affected. Mitigating these collateral consequences calls for a circular, sustainable approach for the management of CDGs in their end-of-life stage with a proactive innovative redesign stage that minimizes their adverse impacts throughout all life cycle phases.

Another innovative measure that can influence the design stage is to include already existing knowledge that is local and environmentally sensitive. The indigenous people living in remote locations have traditional ecological knowledge (TEK), which they use in their daily decision making. They have used this knowledge to make tools for daily usage in local environments that work in a symbiotic manner with their surroundings. Since TEK emphasizes the interconnectedness of all living beings and the importance of living in harmony with nature,[18] it can contribute towards sustainable resource management, waste reduction, and energy efficiency and be a source of inspiration at the design stage of the CDG life cycle.[19] TEK can also guide the selection of materials and products that are both accessible and equitably used by communities at the end-of-life stage of a CDG without having to discard the product entirely (UN SDG 12). This extends product shelf life and potentially serves to reduce greenhouse gas (GHG) emissions, promoting energy efficiency, and enhance local resilience to climate change (SDG 13).[19,20]

One of the challenges of implementing CE is ensuring that marginalized communities, particularly rural and indigenous

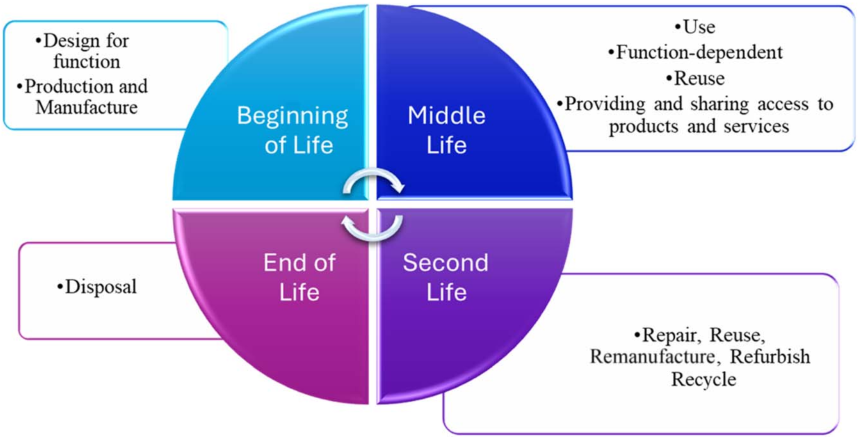

Fig. 2 The typical life cycle of consumer durable goods.

populations, have equitable access to sustainable infrastructure and policy support.[21] This study advances the discussion by showing how localized, TEK-driven CE strategies can bridge this gap, fostering a more contextually sensitive approach to sustainable consumption and production. This review aims to focus on the strategic application of CE principles to the life cycle management of CDGs in the context of northern and rural Canadian communities by highlighting the need to integrate TEK principles for an inclusive and just transition towards net-zero. It compares the global and Canadian contexts of two life cycle stages of CDGs, the design and production and the use stages, to identify the barriers to circular and sustainable systems in particular for the northern remote rural communities inhabited by predominantly indigenous people.

2. Circular systems and the circular economy

The International Standards Organization (ISO) defines the Circular Economy (CE) as an economic system that is embedded within the social and environmental systems (Fig. 3) and that maintains a circular flow of resources, by recovering, retaining or enhancing their value, while contributing to sustainable development.[22] ISO recently introduced the first standard for CE, the ISO 59004, which provides the above international definition of the circular economy and identifies six complementary and interconnected principles of (i) systems thinking, (ii) value creation, (iii) value sharing, (iv) resource management, (v) resource tracking, and (vi) ecosystem resilience within the three circular systems that are interdependent (Fig. 3). The economic system is nested primarily within the social system and both are encompassed by the planetary environmental system (Fig. 3), clearly demonstrating that the social system and the economic systems can only exist within a healthy environmental framework.

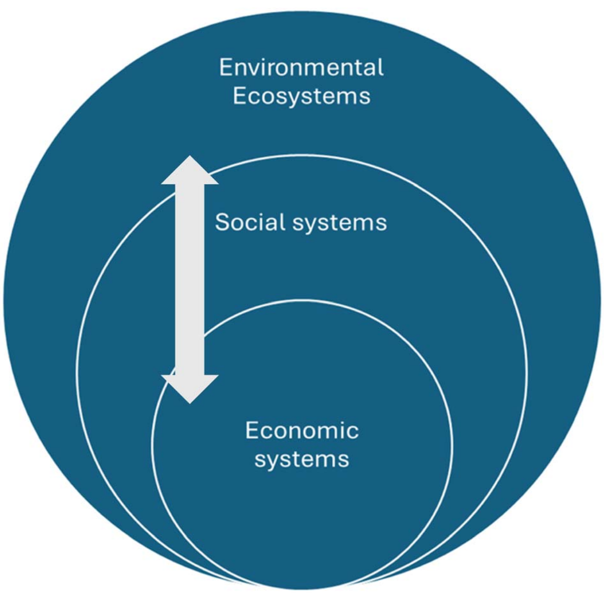

Fig. 3 The interdependent circular economic, social and environmental systems for sustainable development.

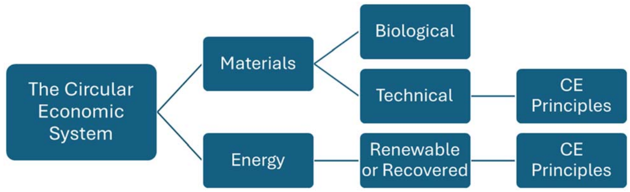

Fig. 4 The circular economic system.

The CE principles impel the use of various complimentary tools for evaluating threats to planetary boundaries including biodiversity, resource and energy flows. The CE standard encourages the use of life cycle assessment (LCA) at all stages of the product or process life cycle to align with these principles. One way to evaluate the resource flows is to ensure that virgin resources and extraction for production are kept as low as possible and energy flows are also circularized to minimize waste, losses and release from the economic system, leading to both social and environmental benefits. A successfully implemented, quantified circular economic system then amplifies the three pillars of sustainability positively.

The circular economy places a high value on conserving products, materials and energy. It differentiates between end-of-life mechanisms for materials that can and cannot be processed or decomposed by living organisms.[23] It classifies the former as the biological materials and the latter as technical materials (Fig. 4). Living organisms such as microbes, decompose waste, whereas technical materials need to be processed either in a landfill or circularized through re-design following CE principles to minimize resource leakage.[11] Applying the CE priorities from ISO 59004 to technical materials such as CDGs, prioritizing concepts of refuse, rethink, source, reduce, repair, reuse, refurbish, remanufacture, repurpose, cascade, recycle, recover energy, and re-mining is essential.[24]

2.1 Consumer durable goods and their life cycle in the circular economic system

Mass production and growing prosperity in the 1950s led to the development of the modern consumer society, encouraging the 'consume and throw away' mentality. It encouraged consumption and planned obsolescence to sustain consumption. Planned obsolescence is an intentional production of goods and services with short productive and economic lives, stimulating consumers to repeat purchases frequently,[25] increasing consumer debt, especially among the most vulnerable. Short product life also affects product quality; for example, battery failure in electronic devices such as smartphones, phasing out of operating system updates and older models slowly becoming non-functional over time[26] despite their materials being robust and useful. Also, large appliances like washing machines become useless when one part fails, for example, when the sealed drum has issues, it becomes economically unfeasible for the consumer to repair or replace it, decommissioning the entire machine.

A circular system does not replace traditional systems but aims to integrate reducing, reusing recycling, and recovering of materials in the current established systems, eventually prioritizing the conservation of natural resources while incorporating economic, social, and environmental values at every stage.[27] In preparation for the production phase of the life cycle (Fig. 2), materials are mined and extracted from the earth, which are eventually discarded as waste.[11] Reintroducing the materials in the production phase of the life cycle again using a CE approach is expected to reduce the burden on mining and extraction and associated environmental, social, and economic harm and loss.[15,28–31] Circular products and systems can be designed to prevent planned obsolescence in the production stage by ensuring a better, durable product design, by providing the consumer with useful information, by standardizing technical designs for the benefit of the consumer in the use phase, and introducing cost-efficient reparability of products in the second life stage.[25] At this stage, the existing CDG design models are not conducive to repair and reuse due to the modular design and proprietary nature of production methods. The training and infrastructure required for repair and recycling are lacking especially in less densely populated communities. Therefore, improving access, equity, capacity and other logistical resources is crucial for the successful adoption of CE in these communities.

3. Challenges with CDGs in the current linear economy

3.1 Environmental challenges from CDGs

Just as the waste from discarded CDGs such as refrigerators, washing machines, dryers, heaters, or mattresses lies visibly on the land due to the inaccessibility of recycling and recovery facilities, particularly in remote locations, the toxic burden from hazardous elements also leads to undesirable adverse impacts.[17] The contamination of local terrestrial and aquatic ecosystems and bio-magnification of the contaminants in the food chain particularly affect indigenous people who rely on local traditional land-based and marine food. Electronics and large and small appliances, among other consumer durables, have raised significant concerns regarding human health and the environment. For instance, electronic waste (e-waste) from products like smartphones and electronic parts in large appliances contain hazardous substances that pose serious health risks, including neurological damage, kidney disease, and cancer.[32] Local garbage collectors and workers who handle e-waste are at risk of exposure to over 1000 harmful substances, including lead, mercury, and polycyclic aromatic hydrocarbon contaminants. The disposal and decay of these goods release toxic substances into the environment, contaminating soil and water and entering the food chain, affecting both wildlife and humans.[33] In addition to contributing to environmental degradation, the beginning-of-life stages, especially the production process stage itself, increase greenhouse gas emissions and contribute to climate change. The mining and extraction of raw materials for these products often lead to habitat destruction, loss of biodiversity, and water pollution, severely impacting ecosystems.[34] In the middle life cycle stage (Fig. 2), the consumption of energy and water associated with these consumer durables is significantly higher in areas with inefficient infrastructure, which exacerbates environmental and health problems for these vulnerable populations.[35] As a result, environmental damage can worsen, contributing to habitat destruction and climate change impacts, which, in turn, can have an adverse effect on population health.[17]

The contamination of soil and water caused by improperly disposed appliances can have long-term effects on local ecosystems. Degradation of the environment can disrupt traditional land-based activities and further threaten food security and cultural practices. The combination of these factors – from production to disposal – contributes to broader environmental concerns, such as habitat destruction and biodiversity loss.

3.2 Recycling challenges for CDGs

Several challenges exist when it comes to recycling consumer durables, including electronics and large household appliances, primarily because of their complex designs and the presence of numerous hazardous materials. Toxic components in these items like lead, mercury, and flame retardants pose major challenges while separating various components, particularly when safety regulations are not in place.[36] These hazardous substances require specialized procedures for safe extraction and disposal to prevent environmental contamination and health risks to workers and the community.[37] The diversity of materials used in CDGs, including plastics, metals, and electronic components, further complicates recycling efforts. This material complexity necessitates sophisticated and often expensive recycling technologies to effectively separate and recover useable materials.[38] It is also important to prioritize end-of-life disassembly and material recovery when designing products, enabling efficient repurposing, reusing and recycling processes.[39] Management of materials at end-of-life are more pronounced for rural, remote and indigenous communities due to the factors iterated above. Table 4 lists the various challenges associated with the recycling of CDGs in the current linear economy, with a particular focus on challenges in remote, rural settlements.

4. Traditional ecological knowledge in an emergent circular economy

The aforementioned challenges related to CDGs are more complex in remote and rural communities, including indigenous population, who follow a different paradigm of spiritual and environmental stewardship of the land. Hence, rural and indigenous communities face distinct challenges regarding CDGs. As a result of a lack of repair facilities and waste management systems, these communities often encounter difficulties in accessing, maintaining, and disposing of CDGs. The inability to purchase and replace CDGs in rural areas is

Table 4 Repair and recycling challenges for CDGs in rural settlements

Challenges in recycling CDGs	Description of challenges	References
Lack of facilities and technicians for repair	Rural areas often have few shops that offer repair services for appliances and electronics. Several reasons can explain the shortage of such shops and technicians in rural areas • The low population density of these areas makes it challenging to sustain repair businesses economically • Low wages and limited opportunities for career advancement need to be improved in attracting and retaining skilled technicians • Rural areas lack training facilities for developing local talent	40 and 41
Lack of specialized equipment Non-recyclable materials	Consumer durable goods often contain materials that are not recyclable, such as certain plastics and liquids, making separation and processing challenging without specialized equipment	42
Insufficient volume for economic viability	In rural areas, there is often a low population density, resulting in insufficient volumes of recyclable materials to justify collection and processing costs	38 and 43
Low market demand for recycled materials	Recycled materials are often perceived as less desirable compared to buying second-hand goods at full price, also making them less attractive than virgin materials for businesses	44 and 45
Limited access to recycling infrastructure	Remote rural communities often lack recycling facilities, making it difficult and costly to transport recyclable materials for processing	42 and 43
Lack of education and awareness about recycling	Many people are unclear about what items are recyclable leading to the inclusion of non-recyclable materials in the recycling stream, contaminating recyclable materials and damaging recycling equipment and machinery	43
Loss of traditional knowledge and with modernization	Modern CDGs rapidly replace traditional skills and knowledge used for creating, maintaining, and repairing traditional tools and items in remote and indigenous communities. Consequently, long-standing cultural practices, economic systems, and relationships with the local environment are altered by this shift. Increasing consumption of modern, durable goods lead to waste management issues in remote areas that are not equipped to handle them efficiently	46 and 47

partly due to lower average incomes, higher transportation costs, and fewer retail options compared to urban centers.[48]

These environmental changes can profoundly impact the well-being of indigenous communities with strong spiritual and cultural ties to the land. There is also a growing concern over consumer durables' energy and water efficiency, particularly in communities with limited resources.[35] The water usage associated with durables such as washing machines and dishwashers can strain local water supplies, which are often under pressure due to agricultural demands and climate change.[17]

Traditional Ecological Knowledge (TEK) is the accumulated knowledge and practices of local communities, rich in culture, customs and environmental sensitivity that are passed from generation to generation, evolving with the changes in the community.[19] TEK emphasizes the interconnectedness of all living beings and the importance of living in harmony with nature.[18] The integration of TEK with scientific approaches is recognized as a valuable resource for climate change solutions.[19] Collaborative efforts involving indigenous communities have been shown to lead to more effective and culturally appropriate climate change policies and practices, respecting their rights and ensuring equitable outcomes.[49,50] TEK offers valuable insights into sustainable environmental management because it is based on centuries of observations, practices, and cultural understandings of indigenous communities.[49,51] Contributions from TEK have been particularly relevant in developing urban green areas, awareness-raising, water and energy saving, the cultivation of more resilient agricultural species, and entomological surveillance, however the uses of TEK for the design of CDGs is not known and has not been used to inform the development of existing products and processes of emergent appliances in circular economy.

In Canada, TEK is being increasingly recognized and incorporated as part of the Canadian environmental management and conservation effort. The indigenous communities collaborate with scientists and policymakers to integrate their time-honored practices and observations into climate change solutions and sustainable resource management. The Nature Conservancy of Canada (NCC) has forged partnerships with indigenous peoples, combining Western scientific approaches with traditional knowledge in conservation projects. This integration of TEK is enhancing conservation efforts and contributing to reconciliation between indigenous and non-indigenous communities in Canada.[52,53] Similar concerted efforts and policy facilitation are required for the integration of TEK in sustainable circular strategies for CDGs.

Apart from product design, TEK has the potential to promote sustainability in the use phase and the end-of-life phase of the product life cycle. CDGs such as washing machines that are widely used in northern rural communities, use a lot of water

Table 5 Integration of TEK at the various life cycle stages of CDGs

Life cycle phase	Description	Integration of TEK principles	Example	References
Beginning of life Design for function	Function & quality in design	Sustainability and respect for environment can be integrated	Leap is involved in the development of circular business models, particularly in the context of packaging for household appliances using alternative cellulose fibers it emphasizes sustainable production, focusing on businesses with methods that allow for the sustainable regeneration of natural resources. This approach aligns with the principles of the CE, which emphasize resource efficiency and waste reduction	54 and 55
		Equitable use, gender sensitivity, geriatric sensitivity and culturally responsive design can be considered		18 and 56
Production & manufacture	Demand for raw materials	Equitable use and consideration for benign production that is sustainable, water and energy efficient can be integrated. Local biomass sources for energy flows can be incorporated in the infrastructure	British Columbia's Coastal First Nations have been at the forefront of implementing TEK into ocean management practices. Their Guardian Watchmen program uses traditional stewardship practices and modern conservation techniques to help monitor and protect marine ecosystems. This program enables indigenous communities to track changes in ocean temperatures, monitor fish populations, and adopt sustainable harvesting practices	57–59
		Historical background knowledge with modern technologies can be merged		47 and 51
		Nature-compatible end-of-life scenarios can be incorporated especially for emergent technologies such as renewable energy products		19 and 60
		Energy source options can be included allowing for function with various sources and intensity variations		20 and 23
Middle life	Use	Appliances as a service, incorporate TEK into usage practices and maintenance, enable customization to suit local environmental conditions and cultural needs, develop shared/second-hand use models, utilize traditional skills to integrate repair and maintenance practices	HOMIE provides appliances as a service, which stimulates sustainable usage of appliances. It provides appliances as a service, which stimulates sustainable usage	61–64
Second life		Pay-per-use, collaboration for upcycling, sharing systems, material substitution to recycled or renewable materials, refurbishing	The Share, Reuse, Repair Hub was first launched by the Circular Innovation Council in 2022, with funding from York Region's Circular Economy Initiatives Fund, as a community-based virtual resource to easily access share, reuse, and repair services in their community. It also provides a platform for local businesses to amplify their role in the CE	54, 55 and 65–69
End-of-life		Benign biodegradation	Accus is a small Swedish company that has been working actively to develop a circular business model for light signs. They have demonstrated a strong commitment to sustainability by using recyclable and used materials in their production. It has taken the company creative methods and a proactive mindset to achieve circularity, with a special focus on finding recyclable aluminum, which has been a challenge	—

Table 6 Aligning CE principles established by ISO 59004 with CDGs integrated with TEK for rural communities

ISO 59004 principle	CE principles	Description	References
Systems thinking	Designing out waste	**Role of TEK in sustainable management:** • Guides the sustainable management of biological materials, which is central to the circular economy **Contribution to consumer electronics:** • Uses traditional practices and materials to develop long-lasting and sustainable consumer electronics **Measures for sustainable electronics:** • Use biodegradable materials • Design products that are easily repaired and recycled • Incorporate energy-efficient components	18, 23 and 49
		TEK often emphasizes: • The use of every part of an animal or plant • This approach aligns with the CE principle of designing out waste **It can be particularly transformative in:** • Rural communities • Remote communities • These areas often have limited access to markets and resources	18, 23 and 49
Resource management	Keeping products and materials in use/community-based approaches	**Community decision-making in TEK:** • Involves inherent community-based decision-making processes **Support for localized circular economy:** • Enhances localized CE initiatives through community involvement **Development of local sharing systems:** • Facilitates the creation of local sharing systems for tools and resources • Reduces the need for external inputs • Minimizes waste by leveraging local resources	11, 18, 23 and 49
Ecosystem resilience	Extending product lifespan	• The design of durable products and the ability to repair them are essential in remote areas where replacements are not readily available **A contribution of TEK can be made by:** • Providing insight into the properties of natural materials • Traditional crafting techniques that result in more durable products	11, 18 and 23
Value sharing	Localizing resource loops	**Communities can minimize emissions by:** • Focusing on local resource loops and reducing their dependence on external goods. For example, local recycling programs tailored to a community's specific needs and outputs can keep materials in use locally and support local industries	11, 20 and 23
Value creation	Integrating renewable energy sources	Remote communities must incorporate renewable energy sources as a critical component of CE **A TEK approach can:** • Guide the sustainable harvesting of biomass for energy production or the design of structures in accordance with passive solar principles adapted to local conditions	20 and 23
	Creating and maintaining local jobs	**CE provides opportunities for job creation in indigenous and remote communities through:** • Repairs, refurbishments, and recycling of consumer durable goods • Creating local centers for these activities can reduce waste and bolster local economies with new skills and professions • Reduces the need for transportation and related carbon emissions, making it both an economically and environmentally beneficial model	11, 23 and 49

Table 6 (*Contd.*)

ISO 59004 principle	CE principles	Description	References
Resource tracking	Reducing reliance on external resources	**Logistical challenges in remote areas:** • Transportation of goods is costly and adds to the environmental footprint • Emissions and infrastructure demands are significant concerns **Benefits of a circular economy approach:** • Maximizes the lifespan of consumer goods through repair and refurbishment • Reduces reliance on new goods and decreases transportation needs • Promotes durability and sustainability of products **Promotion of local solutions:** • Encourages local solutions to minimize frequent transportation • Aligns with themes of incremental learning and sustainable practices observed in indigenous communities **Environmental harmony:** • Emphasizes the balance between local solutions and environmental well-being, as discussed by Turner & Berkes (2006)	17, 23, 49 and 73

and energy in their operation. TEK offers practices like the traditional management of water resources through terracing and the use of renewable energy sources like biomass, which indigenous communities have used sustainably for generations. Therefore, integration of TEK principles in the use phase, second life phase and the end-of-life (Table 5) of the consumer durable life cycle (Fig. 2) would contribute to mitigating the undesirable environmental impact and managing water and energy resources.

The design phase of CDGs is very crucial since function and quality for the next generation products and their uses are integrated. It is in this phase that sustainability and respect for the environment and equitable uses and end-of-life of the products require to be incorporated especially with the emerging technologies such as renewable energy products in the CDG categories.[56] Integrating TEK with modern technologies would benefit equity and sustainability at all stages of development of the product life cycle of CDGs. The rich, and culturally responsive history of TEK, can guide the resource conscious design of products and processes can be implemented in these phases.[18] This can effectively decrease the demand for raw materials, mitigating emissions and adverse environmental impacts from mining, extraction, production and energy use and maximize the use of local resources and energy loops within these communities.[60,70] One of the most important guidelines from TEK for the design phase is the cultural, gender, geriatric and environmental sensitivity in the product design that can create a product that can be used equitably and in an inclusive manner rather than focusing only on function and price of the product. This in turn will also promote the responsible use of raw materials during both production and manufacture phases of the product life cycle.

5. The circular economy and TEK in northern rural and indigenous communities

There is a knowledge gap concerning the application of CE principles to the life cycle of CDGs in the Canadian context. Due to its vast and varied geography, Canada faces unique challenges when it comes to implementing CE, especially in remote, rural, and indigenous communities, where recycling and repair facilities may be limited, and environmental sustainability is imperative for maintaining traditional lifestyles and food security. Research indicates that Canada's northern rural and indigenous communities are particularly susceptible to contamination due to nearby landfill waste contaminating their food supplies.[71] These communities follow a lifestyle that is markedly different from urban areas, as they are heavily dependent on subsistence activities and closely related to their environment.[72] Additionally, there are significant disparities between urban and rural waste management systems, with rural systems lacking the infrastructure and technological support found in urban settings, increasing environmental and health risks.[48]

Incorporating TEK along with the principles of a circular economy provides a potential avenue for achieving sustainability in rural and indigenous communities. This approach utilizes local expertise and resources, ensuring conservation and social-economic resilience.[20] Therefore, the shift towards a circular economy does not merely represent a technical or economic adjustment but a deeper cultural and ecological integration, where TEK can play a pivotal role in shaping sustainable futures. This can help strengthen the treatment of CE aspects in remote rural and indigenous communities. Table 6 shows how TEK and CE intersect with respect to communities, highlighting rural communities in particular. The use of TEK can complement efforts in making consumer products more sustainable, especially regarding resource use, product longevity, design for end of life, and the reduction of adverse environmental impacts. Using this approach is critical to address the broader environmental challenges identified through life cycle assessment studies, which have highlighted significant concerns regarding the consumption of water and energy during the lifetime of household appliances. These findings underscore the need for a shift towards more sustainable practices in producing and using consumer goods, where TEK can provide valuable insights and methodologies.[23,57,60]

Rural and indigenous people face distinct difficulties and opportunities concerning the consumption of CDGs, and tailored environmental measures must be formulated with the knowledge and support from the communities. As shown in Table 2, major appliances, furniture, and miscellaneous durable goods generate significant waste with recycling rates varying greatly between categories. For instance, 58% of major appliances are recycled, but only 5.6% of small appliances are recovered. These issues emphasize the need to develop better recycling technologies and infrastructure for recycling processes, particularly in rural areas where such facilities are scarce.[43] Thus, it explains the need for better, less wasteful manufacturing methods and more mindful, engaged consumption. Concerning these aspects, avoiding such situations is very important in order to prevent severe health and environmental issues, especially in remote areas where there are several issues regarding a lack of repair service facilities, low recycling amounts, and erosion of traditional skills for repairing and maintaining durable goods.

Innovative approaches, such as regional cooperation, mobile recycling units, and community-based initiatives, are emerging to address these issues. Rural, remote communities can benefit from improving education, developing local processing capabilities, and creating incentives for recycling to move towards more sustainable waste management practices and contribute to the circular economy by improving waste management practices (Table 6).[48,71]

The integration of TEK at all stages of the CDG product life cycle will not only positively impact the environment but also foster inclusivity and equity in design, use and safe disposal for rural communities. In the production and manufacturing phase of the product, resource-efficient, reliable, repairable, regenerative, re-purposable and recyclable materials may be used, keeping in mind the production with sustainable biomass residues, renewable energy and equitable end-of-life outcomes for both positive use and environmental impact, all following the guidelines from TEK. The middle phase that constitutes the use phase of the life cycle is a consumer driven phase where the CDG undergoes value creation from use and service. In this phase, TEK can guide the use of renewable energy, the sacred nature of water and therefore the responsible use of the product with a mindset that its use is connected and interdependent on the sharing of resources with other natural species and there is accountability associated with it. The second life is the phase where the product goes through reuse making it the most suitable phase to proactively include product eco-design. In this phase the shift in consumer behavior would also be the most impactful making reuse, sharing, repurposing, pay-per-use, and other collaborative measures to extend the shelf life of a product or service a part of the business models.[54,65–69] The end-of-life phase is another phase where significant development in circular repurposing, refurbishment, redesign, recycling and

Table 7 Case studies of indigenous-led CE projects

Indigenous community organizations	Projects
Daylu Dena (Kaska Nation)	Reducing disposable tableware use and addressing plastic waste through fabric reuse, community recycling bins, a quilt-making program, and reusable dinnerware for gatherings
Gitxaała Nation (Git Lax M'oon)	Expanding a reuse and recycling facility and piloting a method to eliminate single-use containers by integrating commercial dishwashers and reusable containers
Gwa'sala-'Nakwaxda'xw Nations	Reducing and processing plastic waste within the community, installing sorting bins, and providing reusable dishes for community events
Kanaka Bar Indian Band (T'eqt''aqtn'mux)	Providing a commercial dishwasher and reusable dinnerware at the community hall to reduce single-use dinnerware at events
Mother Earth Recycling Inc.	Recycling windshields and laminated glass using specialized machinery, diverting material from landfills and recovering value
Tsleil-Waututh Nation (səlilwətaɬ)	Leading a year-long awareness campaign through community events and school-based activities to prevent and reduce plastic waste
Vitatek Cleaning Solutions	Providing zero-waste, reusable containers for commercial cleaning supplies in the Okanagan region

benign disposal can be integrated. Traditional knowledge of natural decomposition processes may also be used in the design of environmentally safe biodegradable materials.[74] TEK may inform the disposal stage with indigenous waste management practices that have been refined and passed down through generations if practiced[75] or provide culturally appropriate upcycling programs that are aligned with the values and traditions of the local community.[74] Case studies of indigenous-led circular economy initiatives in northern rural Canada incorporating TEK were studied to provide practical examples of indigenous-led circular economy initiatives in northern rural Canada. These projects showcase best practices for addressing waste, recycling, and using sustainable materials in indigenous communities. These projects are summarized in Table 7 and illustrate how TEK is being used as a solution for local sustainability.[76]

6. Challenges in implementing circular practices

The CE, an economic model that aims to reduce waste and optimize resource usage, presents inherent and external challenges to organizations and societies.[77] One of the most significant challenges in a CE is the complexity of supply chains. Global supply chains introduce complexity, as CE principles must be implemented and coordinated across different regions with varying economic, environmental, and regulatory contexts.[77] A circular model requires the integration of recycling, refurbishing, and reuse processes instead of traditional linear models in which products are manufactured, used, and discarded. This integration requires a comprehensive understanding of material flows, product design, and end-of-life management, posing logistical and operational difficulties.[78] To facilitate these processes, CE requires substantial investments in new technologies and infrastructure, a challenge particularly acute for small and medium-sized enterprises (SMEs) with limited financial resources.[79]

Another critical challenge is changing consumer behaviors. Circular models depend heavily on consumer participation in recycling and product return schemes. However, changing consumer habits is a slow and complex process, often hindered by a lack of awareness or incentives.[29] A variety of factors can influence this transition, including policy frameworks, market demand, and technological solutions. In addition to investing in research and development, the CE may require new, more sustainable products and processes.[80] In addition, regulatory frameworks play a deciding role. The absence of supportive legislation or conflicting regulations can prevent circular practices from being adopted. Effective policies encouraging circular economy initiatives, such as extended producer responsibility or incentives for sustainable product design, are crucial.[12]

Addressing the skills gap is a crucial part of transitioning to a CE. Business models and processes inherent to this system require specific skills in areas like sustainable design, waste management, and reverse logistics.[13] The CE model presents a unique set of challenges and opportunities for rural communities. Geographic isolation and limited infrastructure often exacerbate the complexity of these supply chains, making the implementation of recycling, refurbishing, and reuse processes more challenging.[77] SMEs in rural areas may face significant financial obstacles when investing in new technologies and infrastructure necessary to implement CE practices. Changing consumer behavior in rural areas can be challenging due to limited access to recycling facilities and product return programs.[79]

Rural communities, however, typically have stronger social ties and a stronger connection to natural resources, which can be utilized to promote the principles of CE. The skills gap in sustainable design and waste management may be more pronounced in rural areas, necessitating targeted education and training programs.[19] Despite these challenges, rural communities have the unique opportunity to implement CE practices, such as local food systems and renewable energy projects, which can contribute to their economic resilience and environmental sustainability.

Numerous technical challenges and issues are also associated with the transition to a CE even though it represents a sustainable alternative to the traditional linear economic model. Designing circular products is one of the primary challenges.[56] This involves creating products that are not only durable and long-lasting but also designed for easy disassembly and recycling. Achieving this requires overcoming significant technical hurdles in materials science and engineering, as well as in the design process itself.[56] Another technical challenge is the need for standardized materials to facilitate recycling and remanufacturing. The wide variety of materials used in products, especially in complex electronics, makes recycling and remanufacturing processes difficult and costly.[15] Moreover, the development of efficient and effective recycling technologies is essential. Consequently, rural communities may rely on less efficient recycling processes that result in downcycling.[81] This challenge requires advanced recycling technologies that can maintain or even improve material quality.

The management of supply chains in a circular economy also presents technical challenges. Managing the return of used products and materials for reuse, remanufacturing, or recycling requires sophisticated logistics systems.[81] Managing circular supply chains in rural areas presents additional logistical challenges due to geographic isolation and limited transportation networks.[82] In order to implement such systems, it is necessary to overcome technological barriers related to the collection, sorting, and transportation of used materials.[29]

The integration of renewable energy sources into circular economy models is another issue. For maximum sustainability, circular economies should be powered by renewable energy for production, use, and recycling. Integrating these energy sources poses technical challenges, particularly in storing and distributing the energy.[77] Rural settings can be particularly challenging when integrating renewable energy sources due to infrastructure limitations and a lack of specialized energy storage and distribution knowledge.[83]

For a better understanding of the concepts discussed regarding the problems, challenges, advantages, and options in

Table 8 Comparative analysis of rural and urban challenges and opportunities in circular economy

Category	Challenges in rural areas	Challenges in urban areas	Opportunities in rural areas	Opportunities in urban areas
Waste management	Limited waste collection; accumulation of discarded goods in landfills or informal dumps	High waste generation; landfills at capacity; difficulties in segregating recyclables	Community-led waste management strategies; reuse and upcycling programs	Advanced sorting technology; potential for high-efficiency recycling
Access to repair services	Lack of repair facilities and trained technicians; high transport costs make repairs costly	Repair services are available but expensive; planned obsolescence discourages repairs	Local training initiatives and community workshops for self-sufficient repair	Government incentives can strengthen repair culture and consumer awareness
Infrastructure & recycling	Scarce recycling facilities; low profitability due to small populations	More recycling facilities but issues with contamination and logistical inefficiencies	Potential for small-scale, decentralized recycling hubs and mobile units	Investment in large-scale recycling infrastructure and product take-back programs
Circular economy integration	Limited policy enforcement and awareness; reliance on external markets for disposal	Strong policy frameworks exist but face bureaucratic resistance from industries	TEK integration for sustainable product lifecycles and repair strategies	More stringent CE policies pushing industries toward sustainability
Economic viability	Small businesses struggle with circular models due to logistical and financial constraints	More investment opportunities but strong competition and regulatory burdens	Circular models can create localized economic resilience and jobs	CE startups have access to investment, innovation, and consumer markets
Community engagement	Traditional knowledge and community-based approaches exist but lack formal integration	Consumer-driven approach to sustainability but lacks community-centered engagement	Stronger community ties facilitate knowledge-sharing and participation	Digital platforms improve engagement in CE initiatives
Sustainability potential	High dependence on local natural resources; risk of depletion without regulation	CE solutions are growing, but urban resource consumption remains disproportionately high	Localized circular strategies promote regenerative land use and conservation	Tech-driven solutions can improve circularity outcomes

rural and urban areas, all the information discussed above, has been summarized in Table 8. This table compares the challenges and opportunities in rural and indigenous communities.

Finally, developing appropriate business models for CE practices is a technical and economic challenge. Traditional business models may not be suitable for achieving circular practices, and creating new economically feasible and environmentally sustainable models is a complex process.[84]

The challenges described above are either amplified or impossible to overcome in the current northern rural communities' landscape without a systemic change. Therefore, a customized, equitable and inclusive solution is warranted for implementing CE in these communities. In northern rural communities in Canada, by integrating TEK,[18] the concept of CE can lead to sustainable and culturally responsive resource management practices. TEK can contribute to CE practices through sustainable resource management, waste reduction, and energy efficiency.[19] For instance, TEK can inform the design of circular systems that mimic natural cycles, such as utilizing biomass residues and by-products as resources, using renewable energy and recycling materials.[19]

7. Conclusions and further recommendation

Adopting an integrated approach that addresses various challenges and leverages multiple strategies to achieve a CE for consumer durables while incorporating TEK is necessary.[19] This paradigm involves embracing both indigenous and national knowledge systems, by factoring them into the design of products, and building circular supply chain ecosystems. This, also requires active participation of consumers, utilising renewable technologies and implementing adequate policies.[15,29,77,84] Organizations can design more sustainable and culturally appropriate products by integrating TEK in product design and lifecycle management, engaging remote and indigenous populations, and applying eco-design methods.[62,85] These efforts are further supported by the development of localized, interconnected supply chains, as well as sophisticated reverse logistics systems.[11,85,86] Also, educating consumers, providing them with incentives, and reporting on progress achieved in implementing such a practice will help facilitate a more active approach to circular economy practices by the consumers.[80,86,87] These approaches are consistent with many of the defined UN SDGs, in particular supporting SDG 12 (Responsible Consumption and Production) since the concept is about eco-friendly design and decreasing the amount of waste produced. It also promotes the achievement of SDG 9 (Industry, Innovation, and Infrastructure) by developing innovative circular supply chains and applying eco-design concepts. Likewise, the integration of TEK and the importance given to public involvement advance SDG 10 (Reduced Inequalities) and SDG 11 (Sustainable Cities and Communities). The advocacy for using renewable energy in the framework contributes to the realization of SDG 7 (Affordability and Clean Energy) and SDG 13 (Climate Action). Furthermore, the focus on local economies, sustainable areas and activities facilitates the attainment of

SDG 8 (Decent Work and Economic Growth) and SDG 15 (Life on Land). Applying these circular economy concepts, including TEK and a sustainable and fair society, where consumerism and industrialism correspond to nature and native principles, can help achieve other SDGS and promote environmental health and economic vitality.[10] It is also important to note that this review analyzes the existing literature using previously analyzed data to draw conclusions about the barriers to implementing a circular economy integrated with TEK in northern rural communities of Canada. Although policy implications that inform improvements and provide recommendations are considered in this review, a systematic policy evaluation is needed to highlight how TEK can be integrated to build an inclusive and equitable CE for CDGs rather than simply relying on indirect regulatory frameworks. Data derived from the literature may be limited in their generic application to all regions as CE strategies must consider regional and local socio-economic, environmental and cultural contexts.

Data availability

No primary research results or no new data were generated for this review. All research analysed has been cited in this article.

Conflicts of interest

The authors declare no conflict of interest.

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