Urban solid waste challenges and opportunities to promote sustainable developing cities through the fourth industrial revolution technologies

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Abstract

Purpose – In less than a decade to Sustainable Development Goals, the urban solid waste (USW) emanating from households, especially in developing countries, calls for concern. Several policies have been suggested and some implemented, but the challenges facing USW management remain, especially in developing nations. Past studies demonstrated that the fourth industrial revolution (4IR) technologies can be used to improve urban public services. The role of 4IR in mitigating the challenges of USW is yet to receive in-depth research in Nigeria. Thus, the study investigated 4IR role regarding mitigating the challenges facing USW.

Design/methodology/approach – Seven cities across Nigeria, including the Federal Capital Territory, were used as the study area to achieve the research objectives via a qualitative research design. Thirty-two semi-structured interviews were conducted from selected regulators, households, legislators, ICT experts, NGOs and waste managers. A thematic approach was adopted to analyse the collated data.

Findings – Findings group the USW challenges into five categories. The 4IR technologies can be used to manage USW; thus, they create an opportunity to integrate and promote sustainable clean cities.

Research limitations/implications – This study is confined to the 4IR role concerning mitigating the encumbrances facing USW in Nigeria and proffered feasible policies to enhance a sustainable healthy environment.

Practical implications – Proffered policy solutions will stir policymakers and construction practitioners to think outside the box and offer and better understand how 4IR technologies can be utilised to mitigate those challenges. The outcome will create sustainable clean cities as part of the implication contribution to the body of knowledge.

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Originality/value – Evidence from the reviewed literature shows a paucity of literature focussed on 4IR roles in mitigating the encumbrances facing USW in Nigeria. Therefore, this study contributes to the existing research work on 4IR concerning its role in enhancing USW in Nigeria and, by extension, to other developing countries.

Keywords Developing cities, Digital technology, Fourth industrial revolution, Nigeria, Urban, Waste management

Paper type Research paper

1. Introduction

Globally, there is an exponential increase in rural-urban migration of people. One of the possible reasons is for greener pasture. Amorim *et al.* (2019) affirmed that the urban population will hit six billion by 2050. This high concentration of people living in cities may pose a serious issue because of the likely increase in USW. The cities may become vulnerable if no sustainable policy to manage the USW generated. Guerrero *et al.* (2013) asserted that urban solid waste management (USWM) for cities, especially in developing nations, is a massive challenge for cities' regulators and implementors due to many reasons. Some of them are insufficient budget, high costs connected to its USWM and communication issues at different phases.

The authors opined that in most urban areas, the metropolises are responsible for solid waste management and are expected to provide an efficient system to the area's residents. Getting this achieved is not without some encumbrances, possibly one of the reasons for the engagement, especially in developing setting such as Nigeria. Yet, the problem persists. Engaging the private sector in waste management improves the efficiency of the system (Oteng-Ababio *et al.*, 2013; Nwachukwu *et al.*, 2017; Oyebode, 2018). The municipal authority and private partners often face issues beyond the ability to tackle (Sujauddin *et al.*, 2008; Amorim *et al.*, 2019). Households USWM may become a severe issue to the future of cities, especially low-income developing countries if no provision for tactical and scientific plans to manage the waste (Umunnakwe *et al.*, 2019). Nnaji (2015) contended that households generate the largest proportion of urban solid waste in most Nigerian cities and more than 50% in organic nature. This submission, amongst others, strengthened the reason this paper focusses on households' USW.

Past studies demonstrated that the 4IR technologies can be used to improve urban public services (Ebekozien and Aigbavboa, 2021), such as telecommunications, housing provision, roads, etc. This revolution is branded by a fusion of technologies that are "*blurring the lines between the physical, digital, and biological spheres*" (Schwab, 2016, p. 1). This technology generates new prospects, and developing nations like Nigeria can affiliate with advanced nations by accepting blockchain, big data analytics, artificial intelligence, amongst others (Manda and Dhaou, 2019). These are some emerging technologies, and taking benefit of this high-tech revolution can advance the social and economic presence via a transformation towards sustainable cities. The authors confirmed that the United Nations recognised the power of 4IR technology and was adopted by member states in achieving the Sustainable Development Goals (SDGs). This paper, amongst others, intends to proffer policies that will promote the use of 4IR technologies in managing USW generated from households. It may successfully achieve the SDGs connected with urban and its environs before the year 2030.

The United Nations News Centre (2018) avowed that SDGs are the outline to accomplish an improved sustainable future for all. Ebekozien *et al.* (2019a) found goal nos.3 (good health and well-being) and goal nos.11 (sustainable cities and communities) amongst the goals that have interconnection to increase residential accommodation provision, employment prospect, and the impact would be economic development with a sustainable livelihood. This validated World Bank Press Release (2017) and Gambo *et al.* (2019) submission. They opined that an

inhabitable environment enhances the well-being of the residents. In Nigeria's context, the 4IR technologies and creating sustainable clean cities have to provide solutions and opportunities to deal with those challenges. It is one of the justifications for the study. Also, this paper will fill the literature gap concerning the role of 4IR in mitigating the challenges of USW. It will lead to promoting sustainable clean cities across a developing setting like Nigeria. Therefore, the paper seeks to identify the challenges and explore the role of 4IR technologies emerging from the field to deal with the issues facing households USWM via stated objectives as follows:

(1) To examine the challenges facing households USWM in developing cities across Nigeria.

(2) To explore the role of 4IR technologies in mitigating the challenges facing households USWM in developing cities.

2. Theoretical framework

This paper's framework was modified from the Integrated Sustainable Waste Management Framework. It is a framework that provides academic learning of the multi-dimensional schemes in an integral pattern. The WASTE advisers on city environment and development developed the framework (WASTE, 2004). In the mid-1980s, the framework was further developed by organisations working in developing nations via the Collaborative Working Group (CWG) on SWM (Guerrero *et al.*, 2013). The framework identified the stakeholders interested in USWM elements, final disposal and the "lenses" via which the mechanism is analysed as the three critical dimensions (ISSOWAMA Consortium, 2009; Wilson *et al.*, 2009; Scheinberg *et al.*, 2011). This paper is set within a modified USWM framework, as presented in Figure 1. Thus, focus on investigating the challenges facing households' USWM and exploring the role of 4IR technologies in mitigating the challenges in developing cities. The paper intends to promote the use of 4IR in USWM. In the framework, Guerrero *et al.* (2013) identified waste generation and separation, collection, transfer and transport, treatment, recycling and final disposal as the main elements of waste management systems. This paper intends to explore the issues confronted with each of the elements of the waste management systems and proffer solutions by using the 4IR technologies to mitigate these challenges.

3. Literature review

3.1 Urban solid waste management background

Several studies have been conducted within USWM. Many of the papers tackled specific issues within the waste management system. The mechanism to transport the waste was one of the early papers that emerged within waste management (Truitt *et al.*, 1969). Waste management authorities conducted the types and quantities of waste generated in a specific region and by different categories of income earners (Elsaid and Aghezzaf, 2015). Bertazzi and Speranza (2012) studied modelling the waste management issue to express the economic evaluation of the mechanism, including the gathering, transportation and discarding. Some scholars such as Bidart *et al.* (2013) and Melikoglu (2013) compared different recycling techniques or energy recovery options, or different composting methodologies in their papers. In the works of Eriksson and Bisaillon (2011) and Achillas *et al.* (2013), the authors worked on the waste management system and how to make a decision concerning waste management. Table 1 shows the summary of identified issues facing households USWM in some developing cities.

Elsaid and Aghezzf (2015) developed an integrated sustainable waste management framework, focussing on achieving economic and environmental aspects of sustainability.

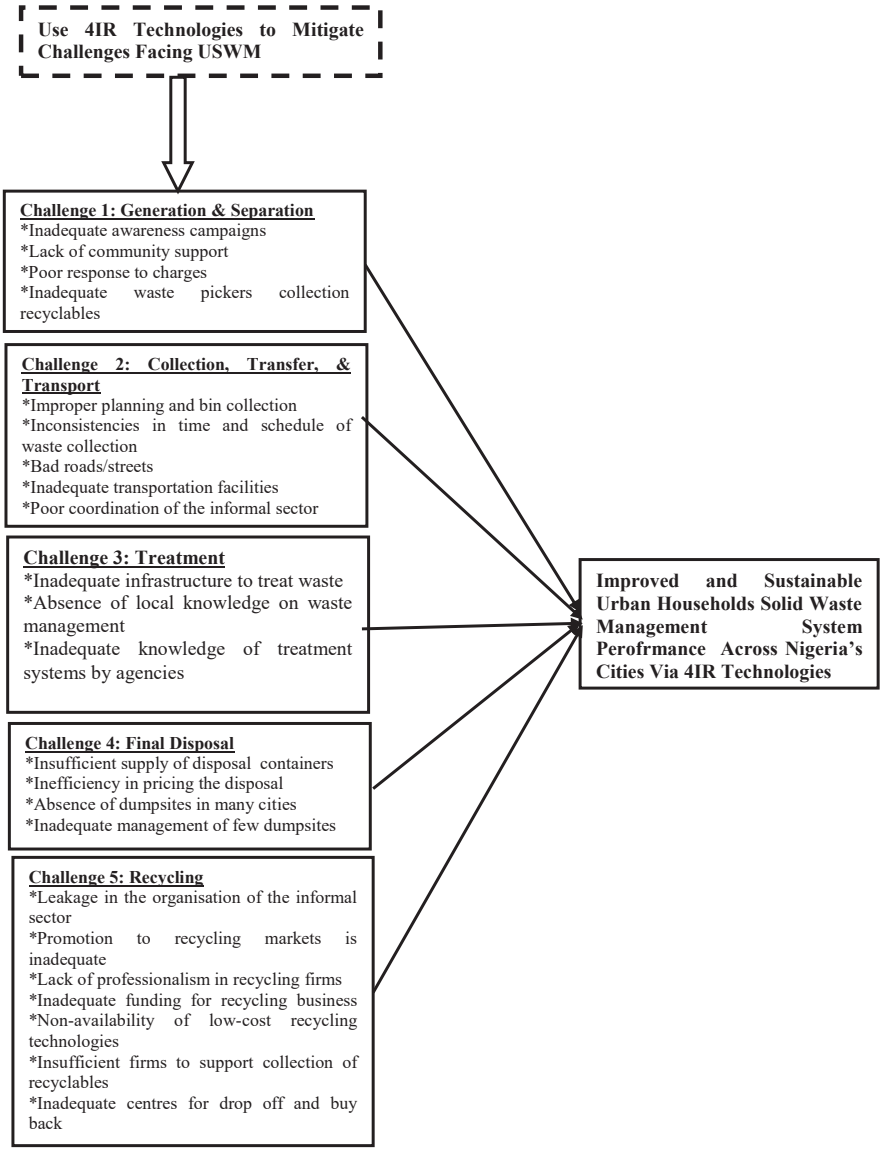


Figure 1.
Sustainable urban waste management framework

Source(s): Modified from WASTE (2004), ISSOWAMA Consortium (2009), Guerrero *et al.* (2013), and Elsaid and Aghezzaf (2015)

The framework emphasised recycling and examined the factors affecting the performance of the waste management system. Challenges associated with the stakeholders such as government at different levels, municipal agencies, NGOs, households, private cleaning companies, ministries of environment and health were identified. The authors identified the issue of sustainable waste management strategy regarding waste producers' willingness to

Source	Country/City	Challenge(s)
Samwine *et al.* (2017)	Accra, Ghana	1. Increase volumes of waste due to faster rate of generation and the high cost of waste management. It cut across many cities, not only in Ghana, but all over Africa, Asia, South America and even some European countries 2. Prudent waste management processes are very costly whose short term returns are intangible 3. Ghana is beset with the challenge of modern technology which range from equipment and tools to the break-down of waste collection trucks and dustbins due to poor maintenance to inadequate skills required in tackling the solid waste menace 4. The challenge of poor attitude of persons in complementing the efforts of waste managing bodies 5. There is lack sufficient engineered landfill sites for proper treatment and disposal of solid waste
Kubanza and Simatele (2019)	Johannesburg, South Africa	1. There is the weaknesses and inadequacies of national and local government institutions in the face of rapid urban change 2. There is the lack of political will and knowledge
Teshome (2021)	Ethiopia	1. The present waste management system can be described by 3 I's (Irregular, inadequate, and inefficient) 2. There is inconsistent collection and low coverage 3. There is technical frailties and inadequate enforcement of laws
Zainu and Songip (2017)	Malaysia	1. High cost in managing waste 2. Inadequate landfills
Malinauskaite *et al.* (2017)	European countries covered (Estonia, Greece, Italy, Latvia, Lithuania, Norway, Poland, Slovenia, Spain, and the UK)	1. Lack of cooperation between different lawyers of multi-governance in waste management and the political-will 2. Having issues with cost-efficient and socially acceptable 3. Issues related to technological advancement

Table 1. Summary of identified challenges facing households USWM in some cities

pay for the waste produce and legislation concerning solid waste transfer and dumping. It is germane and possibly lax in Nigeria's context. Guerrero *et al.* (2013) identified the challenges facing SWM in developing cities. Apart from being a review, the study excluded Nigeria. The authors identified the issues in line with the classified process of the integrated sustainable waste management framework. They are generation and separation; collection, transfer and transport; treatment; disposal; and recycling. Some of the challenges identified for generation and separation include inadequate awareness campaigns, lack of community committee support and poor response to charges. Improper planning and bin collection, inconsistencies

in time and schedule of waste collection, bad roads and inadequate transportation facilities were identified as the issues associated with the collection, transfer and transport. For treatment, the issues are inadequate infrastructure, absence of local knowledge on waste management and inadequate understanding of treatment systems by agencies. Insufficient supply of containers and inefficiency in pricing the disposal was identified as the issues facing the disposal phase of the integrated sustainable waste management.

Last but not least of the phases is recycling. Guerrero *et al.* (2013) identified leakage in the organisation of the informal sector, promotion to recycling markets is inadequate and lack of professionalism in recycling firms as the issues surrounding the recycling phase of the integrated waste management system. Others are inadequate funding for recycling business, nonavailability of low-cost recycling technologies, insufficient firms to support the collection of recyclables and inadequate centres for drop off and buyback. Nnagi (2015) found insufficient funding, inadequate manpower, insufficient equipment, insufficient dumping sites, bad street/road networks, inadequate maintenance of working equipment, lax guidelines and laws relating to SWM and weak collection technique and disposal as the major challenges confronting proficiency in USWM in Nigeria. The author claimed that between 30 and 60% of wastes is not collected because of the inefficiencies in the system. This category of people adopts an unconventional approach to dispose of their waste. The current research will further study this category of problems, emphasising the role of 4IR technologies to mitigate the challenges confronting USWM in a low-income developing setting like Nigeria.

3.2 Fourth industrial revolution technologies background

Recent studies (Schwab, 2016; Ayentimi and Burgess, 2018; Manda and Dhaou, 2019; Ebekozien and Aigbavboa, 2021) have proved the significance of 4IR technologies' importance and how they can be used to leverage development and drive economic and social growth across the globe. Today, the development of the 4IR technology is comprehensive in tackling world challenges using artificial intelligence that involves smart systems as likened to former industrial revolutions that were reinforced by mass manufacture, transportation, speedy electricity consumption and communication expertise consumption (Makridakis, 2017; Naude, 2017; World Economic Forum, 2017). Fascinatingly, 4IR has a variety of innovative technologies that are blending the digital and physical realms. USWM is not exempted but literature is scarce regarding its role mitigating increasing challenges facing urban waste. It is one of the areas of deficit that this paper will address. It is also impacting positively on all disciplines and industries (Ayentimi and Burgess, 2018).

Schwab (2017) opined that the digital revolution of the 4IR challenge goes in-depth to represent how humans should perform in real life. Some scholars, such as the Department of Economic and Social Affairs (2017), Millington (2017), and Peters (2017), have recommended severe penalties of the 4IR in that the fresh wave of the digital revolution impends to allow humans threatened species, disturbs job markets and contributes to rising income disparities and joblessness. It has been projected that about one-quarter of the world's population under the age of 25 will be home in Africa by 2030. World Economic Forum (2017) claimed that the works that ought to be carried out by workers are diminishing with the assistant of robotics and digital equipment. This claim is arguable and not within the scope of this paper.

In the context of this paper, Nigeria remains the giant of Africa. At the same time, Africa is the world's largest continent regarding many nations, with 54 nations (African Development Bank, 2016). It makes Nigeria's one of the major regions with important natural resources and human capital, like other developing countries across the globe. In several fora, 4IR has been argued to drive the development of technologies to strengthen production growth in different sectors (World Economic Forum, 2017). The USWM subsector is not exempted. To achieve this

task, Osabutey *et al.* (2014) and Lee *et al.* (2018) found a wide range of variables as significant constructs influencing the rapidity of technological usage and transfer into an economy. Hensengerth (2018) and Olawuyi (2018) identified empowering regulatory environment, social and economic environment and cost as some of the variables that will influence the swiftness of digital usage. In the opinion of Naude (2017), entrepreneurs are key stakeholders to drive digitalisation and innovation into the market for the growth of the sectors. This is missing in the content of USWM and current literature, the waste managers have not invested enough in USWM. This new technology (4IR technologies) is built on developing ICT competencies and allows a mixture of computational power and new technologies (Makridakis, 2017). Schiuma (2017) asserted that the mixture of computational power and new technologies could transform societal structures and the working environment. The author affirmed that the technology supports digitalisation and is transformative to drive automation and robotics, leading to the advantages of returns-to-scale. Also, the World Economic Forum (2016) is pioneers championing the 4IR highlight. It is because it will grow the competencies of artificial intelligence and robotics in all sectors, USWM inclusive.

3.3 4IR technologies role in USWM

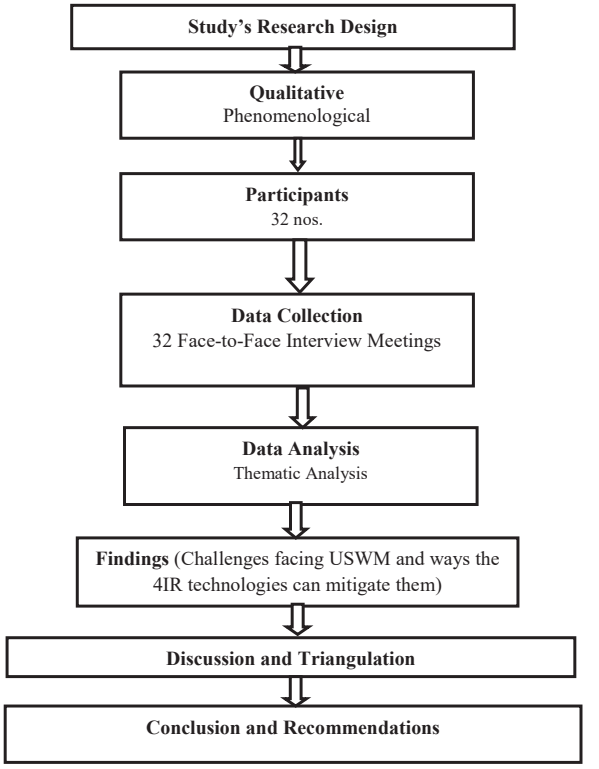
Regarding the role 4IR can play to mitigating the challenges facing USWM, first, the paper identified the major 4IR technologies used in the construction sector. Ebekozien and Aigbavboa (2021) categorised them into smart construction sites, simulation and modelling and digitisation and virtualisation. The technologies enlisted under smart construction sites are radio-frequency identification, modularisation, robotics, Internet of things (IoT)/services, automation, cyber-physical systems and human–computer interaction. Augumented reality, BIM and simulation models were identified as the technologies enlisted under simulation and modelling, while digitisation, cloud computing, big data, mobile computing and social media were grouped under digitisation and virtualisation. Ayentimi and Burgess (2018) found that the significance of the 4IR to sub-Saharan Africa cannot be over-emphasised. The authors agreed that the potential transformation of the technology to overcome present infrastructure shortfalls, including the challenges confronting the USWM, via the use of the innovative technology cannot be under-estimated. The technology can impact all sectors, irrespective of their location. Khandare *et al.* (2018) and Saranya and Vigneshwaran (2020) found that with the help of a simulation model, robot and IOT, a smart dustbin can be developed and used in smart cities for the collection of debris. The robot and IOT are components of the 4IR technologies. It can help manage the waste and the dustbin made smart through the ultrasonic sensor systems. It will mitigate some of the challenges because debris and recycling pickup work are physically demanding, and it exposes waste manager staff to occupational hazards such as nail or piece of bottle injuries (Khandare *et al.*, 2018). The 4IR technology and digitalisation play a pertinent role in waste reduction via improving the city's USWM in terms of public participation in USW separation through the 5 Rs schemes. They are reduction, recycle, reuse, recovery and repair schemes solution (Kurniawan *et al.*, 2021). The authors affirmed that if the target of the 5R recycling rate is to be achieved, incorporating digitisation into the USWM provides the city with a technology-driven waste solution.

The 4IR technologies may enhance the conversion of USW to energy generation. Amo-Asamoah *et al.* (2020) affirmed that the high cost of waste disposal now emphasis the need to reduce, re-use, recycle and recover via the concept of the circular economy. The concept is all about how to use generated household waste to alleviate the poor in the society. Ofori (2016) contended that gasification, combustion, landfill gas recovery and anaerobic digestion are generating energy from solid waste, while International Renewable Energy Agency (2015) affirmed that combustion generates about 90% of biomass energy. Wijenayake *et al.* (2017) found that a smart robotic garbage bin can mitigate issues

associated with improper garbage collection processes in Sri Lanka. It can be achieved because a smart robotic bin has smell control, IOT, human–machine interaction and bin space managing. The smart bin automatically disposes of garbage once the garbage truck arrives. The GPS tracking system allows the position tracking faster. A confirmation signal is forwarded through the Bluetooth communication from the bin to the truck operator after the disposing. It is one of the ideal solutions to mitigate the garbage health-related challenges being faced by developing countries. The IOT, robots, GPS, amongst others, are components of the 4IR technologies.

4. Research method

This study adopted a qualitative research approach. Chandra and Shang (2019) avowed that the qualitative research approach is entrenched in interpretivism. Interpretivism views intuitively as a social variable, and scholars' intention is to understand the meanings of human actions (Schwandt, 2003; Ebekozien, 2021). The paper was addressed from a phenomenologically driven longitudinal viewpoint. Paley (2016) affirmed that the term "phenomenologically" derived the "meaning" of the scenario by interviewing a group of persons. Neale (2018) described the word "longitudinal" as it discovered manners to the occupation over time. Thus, a phenomenology type of qualitative research design was used to achieve the paper's objectives, as presented in Figure 2. Two data collection tools were



Source(s): Modified from Ebekozien *et al*. (2021, p. 11)

Figure 2.
Framework of the paper's research design

adopted. They were the literature review and selected semi-structured face-to-face interviews (Ebekozien, 2020). This paper adopted a purposeful sampling technique. According to Ebekozien (2020), purposeful sampling targets interviewees who are considered prominent and knowledgeable in the subject matter. It validated the submission of Crouch and McKenzie (2006). They affirmed that emphasis that the dynamic qualities are dependent on words, not numbers. Thus, a small sample size is inconsequential. The strength of face-to-face interviews is that the participants can shed light on the concealed information concerning the subject matter (Ebekozien, 2020). As the information sought was only available from a small circle of experts who have been campaigning to use 4IR in urban waste management in Nigerian households, purposeful sampling technique offered the means to obtain reliable perception.

Thirty-two face-to-face semi-structured interviews from selected households, regulators, legislators, ICT experts, NGOs, housing experts, waste managers and environmental experts were engaged. It took place from May 2021 to July 2021 across seven cities in Nigeria, including the Federal Capital Territory, as presented in Table 2: Federal Capital Territory, Kano, Jos, Kaduna, Benin City, Port Harcourt and Lagos. Kano and Lagos have the largest population in the northern and southern cities, respectively, while the other five cities are in strategic positions. It is similar to a study conducted by Ebekozien *et al.* (2019a) that adopted five cities. The face-to-face interview lasted for an average of 70 min, and saturation was achieved. It was compensated with a comprehensive literature review, in line with Gorbacheva and Sovacool (2015). The participants' identities through concealed were considered well-informed regarding 4IR technologies and USW. For example, Participants P9, P20, P25, P26, P27, P30 and P32 have over 25 years of work experience in USWM, while P5 double as a household and a top management staff of one of the private waste firms. Also, P23 is a former senator in the Sixth National Assembly and operates a licence private waste management firm. These participants have been directly or indirectly promoting the use of digitalised technology to manage urban waste. The agitation for the use of 4IR technologies in managing USW is not without some hindrances outside this paper's scope. Concerning ethical matters, the participants were informed about the goal of this paper and agreed to take part without intimidation. The study followed ethics and was approved. The participants' responses were presented in an anonymous form. Apart from a few guided questions as shown in Appendix, the interviews were unstructured, so that the research subject could be discovered in depth from the participants' viewpoint (Creswell *et al.*, 2018).

Regarding the analysed data via thematic approach, words and sentences were allotted a tag. The label was to enhance the generation of the paper's concepts in line with the

	City/Code							
	A	B	C	D	E	F	G	Total
Participant/Rank	FCT	Kano	Jos	Kaduna	Benin city	Port Harcourt	Lagos	10 km
Resident	P1	P2	P3	P4	P5	P6	P7	7
Waste manager	P8	P9	P10	P11	P12	P13	P14	7
Govt agencies	P15	P16	P17	P18	P19	P20	P21	7
Lawmaker	P22 and P23							2
ICT expert	P24, P25 and P26							3
Environment expert	P27 and P28							2
Environment and health NGOs	P29 and P30							2
Housing expert	P31 and P32							2
Total number of participants								32

Note(s): P = Participant

Table 2. Summary of participants' description

objectives. Thus, an open coding system of coding was adopted in the transcription of interview data. Invivo, narrative, emotion and themeing coding techniques were employed (Corbin and Strauss, 2015). One hundred and thirty-four codes were developed and re-organised based on reference, frequency and occurrence in line with the coding. From the 134 codes (such as robotics, IOT, simulation model, ultrasonic sensor systems, 4IR technologies, the Internet, cyber, cyber-physical-systems, USW, smart bin, reduction, recycle, reuse, recovery, and repair schemes, Bluetooth communication, technology-driven waste solution, combustion, landfills gas recovery, mell control, bin space managing, human–machine interaction, GPS, amongst others), 10 categories (such as USW management, generation and separation challenge, collection, transfer and transport challenges, treatment challenges, disposal challenge, recycling challenges, amongst others) were derived and mapped into two themes (challenges facing households USWM and 4IR technologies role in mitigating the challenges). The group discussion approach was used to check the themes by an expert. Also, fears to the validity of results were alleviated through the triangulation of data collection mechanisms (Tajeddini and Mueller, 2009). The analysed data and subsequent presentation of the results were based on the perception of 32 participants.

5. Findings and discussion

This section presents the findings and discussion in line with the paper's objectives. Each theme addresses each objective. Issues affecting households USWM in developing settings like Nigeria's cities concerning the use of 4IR technologies to manage the waste is one of the areas that has been under studied and possibly can mitigate the challenges facing the USWM. This has become pertinent because previous policies and programmes over the past years did not yield the needed outcome. Findings have shown that digitalised technology which belongs to the 4IR works as an end-to-end innovative and digitalised mechanism across the value chain in any sector as revealed. The USWM is not exempted. The following subsections present the two themes results and discussion:

5.1 Theme 1: challenges facing households' urban solid waste management

In this sub-section, five sub-themes emerged as the challenges being faced in managing households' USW in Nigeria's context. Categorising the identified challenges into five sub-themes is one of the germane highlights that emerge from the theme as presented in Table 3 (Columns 1 and 2). Findings grouped the challenges facing solid waste management in developing cities in line with the process of the integrated sustainable waste management framework as developed by WASTE (2004), ISSOWAMA Consortium (2009), Guerrero *et al.* (2013) and Elsaid and Aghezzaf (2015). Thus, the framework was modified and used for this paper. They are generation and separation; collection, transfer, and transport; treatment; disposal; and recycling. Participants P10, P16, P27 and P30 identify inadequate awareness campaigns, household income, lack of community support, poor response to charges, inadequate waste pickers collection recyclables and lack of training on the waste producers; as the challenges associated with "generation and separation phase." This is one of the major groups of challenges that emerged from this paper. Majority of the participants agree that creators of waste, especially in extremely low-income areas are reluctant to pay for the service rendered. Participant P8 says "[. . .] *we operate in four cities across the country, and I am serving in Wuse Township Area, Abuja. The waste generation and payment responses are high here compared to other cities, but the economic value of the business is not encouraging* [. . .]"

Public provision of households' urban waste services, especially in Nigeria, is characterised by little recovery from service receivers (P23). The reason may be inadequate institutional framework and regulatory agencies' capacity to respond to

Challenges in sub-theme	Theme one: Emerged challenges	Theme two: Role of 4IR technologies
Challenges facing "generation and separation phase"	Inadequate awareness campaigns	Digitalisation of the urban waste management sector will enhance communication and improve awareness
	Lack of community support	Creation of digital value chain, a product of 4IR technology will engage stakeholder in participation (P26)
	Poor response to charges	P24 says "*. . . digitalisation will improve service delivery and when there is service delivery, payment will naturally come . . .*"
	Inadequate waste pickers collection recyclables	Smart robotic bin, a component of the 4IR technologies, will eliminate this issue (P27)
	Lack of training on the waste producers	Creation of digital value chain, a product of 4IR technology will engage stakeholder in participation
Challenges facing "collection, transfer, and transport phase"	Improper planning in bin collection	Smart robotic bin, a component of the 4IR technologies, will eliminate this issue (P24, P25 and P27)
	Inconsistencies in time and schedule of waste collection	Smart robotic bin, a component of the 4IR technologies, will eliminate this issue (P24, P25, and P27)
	Bad roads/streets	Simulation and modelling can assist to guide the truck movement (P26 and P28)
	Inadequate transportation facilities	The digitisation, automation, and integration will reduce the numbers of trucks for operations
	Poor coordination of the informal sector	Digitisation and virtualisation will enhance blinding the informal sector into the formal sector with less stress (P31 and P32)
	Shortage of bin for waste collection	With smart robotic bin, shortage of bin will become a thing of the past in solid waste management (P24, P25, and P26)
	Inconsistencies in house numbering	Simulation and modelling can eliminate the inconsistencies in house numbering (P25)
Challenges facing "treatment phase"	Inadequate infrastructure to treat waste	P28 says, "*. . . technology and digitalisation is not about number and size but quality and achieving the task . . .*" the 4IR technologies have these attributes
	Absence of local knowledge on waste management	Cheap social media applications created can improve the local knowledge on waste management (P14, P21, P23, P26, 30 and P32)
	Inadequate knowledge of treatment systems by agencies	Cloud and BIM-based platforms if created can improve the local knowledge on waste management (P10, P12, P14, P23, P26 and P32)
Challenges facing "final disposal phase"	Insufficient supply of disposal containers	With smart robotic bin, shortage of disposal containers will become a thing of the past in solid waste management (P24, P25, and P26)
	Inefficiency in pricing the disposal	Innovative pricing technologies through selection process (P25 and P26)
	Absence of dumpsites in many cities	Mobile digital dumpsites with semi-recycling applications (P26)
	Inadequate management of few dumpsites	Automation of labour-intensive processes using robotics or automated workflows

(*continued*)

Table 3. Summarised main findings

Challenges in sub-theme	Theme one: Emerged challenges	Theme two: Role of 4IR technologies
Challenges facing "recycling phase"	Leakage in the informal sector	Automation, cloud computing, mobile computing, social media, and robotics will mitigate any possible leakage in the informal sector (P6, P9, P12, P24, P25, P28, P31 and P32)
	Inadequate promotion of recycling markets	Social media, mobile computing, and cloud computing (P23, P25, P27 and P30)
	Lack of professionalism in recycling firms	Automation, robotics, cloud computing and digitisation will eliminate professional inefficiency (P23, P24, P25, P28 and P31)
	Inadequate funding for recycling business	On the long time, digitisation, robotic, and mobile semi-recycling plant will bring down production cost (P10 and P25)
	Non-availability of low-cost recycling technologies	Local 4IR technologies should be encouraged via research (P8, P10, P15 and P20)
	Insufficient firms to support collection of recyclables	The automation and robotics technologies will mitigate the challenges of insufficient firms for collection of recyclables (P24, P26, P28 and P30)
	Inadequate centres for drop off and buy back	The human–computer interaction and robotics technologies will render many centres useless (P24, P26, P28 and P30)

Table 3.

environmental waste management and related matter. Findings agree with Guerrero *et al.* (2013), and it was discovered that though USW services are similar to other services regarding the cost, the expenditures are hardly recovered. Rahji (2009) and Igbinomwanhia and Ideho (2014) argued that the generation of households USW and its management are all influenced by household income. Participants across the board agree that there is inadequate awareness regarding the separation of waste. Participant P29 says, "[. . .] *we have recorded some success in this area as part of our cardinal vision to sensitise households the relevance of waste separation to the environment. We have conducted several household waste separation programmes in collaboration with our international partners* [. . .]. "

Findings identify challenges associated with "collection, transfer and transport phase." It includes improper planning and bin collection, inconsistencies in time and schedule of waste collection, bad roads/streets, inadequate transportation facilities, poor coordination of the informal sector, inadequate infrastructure to treat waste, shortage of bin for waste collection and inconsistencies in house numbering. Participant P30 says, "[. . .] *poor supervision and man-power shortage are possible reasons many of Nigeria's urban waste managers are having a 'free day* [. . .]" But this allegation was rebuffed by Participant 8. Evidence from observation shows that there is lax supervision across the seven cities covered. Participant P5 says, "[. . .] *there is a scarcity of waste bins in my neighbourhood. Few households that made an extra effort to provide additional bins do not necessarily imply that wastes deposited therein are collected [. . .]. because of inconsistencies in the collection and some cases, we are told that the truck has developed fault* [. . .]" Majority of the participant agree that there are issues associated with the collection methods. The main collection methods are communal container collection and house-to-house waste collection. Findings agree with Nnagi (2015) and Samwine *et al.* (2017). The authors found that inadequate manpower, insufficient equipment, bad street/road networks, inadequate maintenance of working equipment, among others, contribute to the challenges confronting proficiency in USWM in Nigeria. Inadequate infrastructure to treat

waste, absence of local knowledge on waste management, and inadequate knowledge of treatment systems by agencies emerge and grouped as the "treatment phase." Participant P8 says, "[. . .] *the failure of the government and her agencies to provide us sufficient dumpsites and recycling plant has promoted the 'waste pickers' (informal waste managers). For one, they (waste pickers) are the ones that source separation of waste and resale the saleable. But the system does not recognise them* [. . .]" In the view of P26, P28 and P29, for any technology to work effectively, there should be provision for the selection of waste such as plastic, bottle, paper, steel, etc. It will promote sustainable, environment-friendly cities, reduce waste at source and improve the prospects of success for pre-treatment and treatment technologies.

Concerning "disposal," findings identify insufficient supply of disposal containers, inefficiency in pricing the disposal, absence of dumpsites in many cities and inadequate management of few dumpsites as the challenges associated with the "disposal phase." Participant P14 says, "[. . .] *the problem of households urban solid waste disposal in many parts of Lagos has become one of the most stubborn environmental complications that all stakeholders should give serious attention. It is already beyond what the government can address, but they (governments) can create an enabling environment and driven policies to achieve this goal before the year 2030 [. . .] Are the few dumpsites accessible to the waste operators? Who is managing the dumpsites? How is the waste being disposed of? These and many questions should be addressed via the policies and programmes by the government* [. . .]" Findings agree with Oyebode (2018), and it was found that in many Nigerian cities, the volume of households' USW has overwhelmed urban waste managers' capacity to plan for their collection and disposal because of inadequate facilities. Participant P12 says, "[. . .] *it is not unusual to find urban roads and streets virtually blocked by solid wastes dumped on the road walkway by residents [. . .] possibly because of inefficiency on the part of the waste manager or not willing to pay for the disposal charges* [. . .]. " The absence of proper urban waste disposal can affect the residential quality and the environmental quality of these cities (Participants P1, P3, P16, P26, P29 and P32). Participant P10 says "[. . .] *we have to create our dumpsites and maintain them yet we paid heavily for these during registration, how do you expect us to perform*? [. . .]" The last grouped challenge is the "recycling," and findings identify leakage in the firm of the informal sector, inadequate promotion of recycling markets, lack of professionalism in recycling firms, inadequate funding for recycling business, non-availability of low-cost recycling technologies, insufficient firms to support the collection of recyclables and inadequate centres for drop off and buy back as the challenges associated with "recycling phase." Participant P14 says, "*[. . .]. we can procure dumpsites and install recycling plants, including maintaining the site(s), but majority of us (waste managers/operators) lack the financial capacity. We want to go technological in managing the business like in some advanced countries, but there is no government support. What you read on the pages of the newspaper is different from the reality* [. . .]. " Findings agree Oteng-Ababio *et al.* (2013) and suggested appropriate institutional and financial instruments for the waste sector in African cities since the operators show willingness to invest in digitalised waste management technologies.

5.2 Theme 2: 4IR technologies role in mitigating the challenges facing households USWM

This sub-section approach the role of the 4IR technologies in line with the challenges that emerged from the findings as previously highlighted in Table 3 (Columns 1 and 2), while the role of the 4IR technologies is summarised in Table 3 (Column 3). The major 4IR technologies that emerge cut across the three major categorisation of 4IR technologies as identified by Ebekozien and Aigbavboa (2021) and mentioned previously. Digitalisation, smart robotic bin and digital value chain emerge as the key technologies and concepts that can mitigate the challenges associated with "generation and separation phase" of the households USWM. Participant P7 says, "[. . .] *the 4IR technology is a high-tech strategy, multifaceted, and*

interdisciplinary concepts that have huge technological potential if allowed to operate in any sector, including the households urban solid management [. . .].” Viewpoints from P26 and P28 believe that simulation and modelling can guide the truck movement against bad roads and inconsistencies in house numbering. P28 says, “[. . .] *technology can map the houses and roads through Google map and direction for the suitable roads and link can be given* [. . .].” Findings agree with Jung *et al.* (2013) and described simulation and modelling as significant concepts used to manage the rising complexity of industrial/construction procedures and improve them by setting scenarios and mitigating dangers in the early phases of the process. It indicates from the onset; one can know the locations of potholes and how to avoid them. Participants across the board agree that the digitisation, automation and integration will reduce the number of trucks for operations. Participant P25 says, “[. . .] *the* ‘*smart robotic bin*’ *has a mechanism to compress urban solid waste and has a sensor to indicate that the waste is ready for collection. It will automatically reduce the number of trucks on the road because of the time and well-planned system of waste collection* [. . .]” Findings agree with Saranya and Vigneshwaran (2020), and it was found that with the help of a simulation model, robot and IOT, a smart dustbin can be developed and used in smart cities for the collection of debris. Regarding the inadequate transportation facilities, apart from reducing trucks for the operations because of the digitisation, automation and integration, the safe operation of the chain value system will improve (P20, P23, P27 and P29).

Three of the major technologies emerged regarding how the 4IR technology’s role can mitigate the challenges associated with the “treatment phase.” They are smart robotic bins used to mitigate the inadequate infrastructure to treat waste, cloud computing and BIM-based platforms to address the issue of absence of local knowledge on waste management and inadequate knowledge of treatment systems by agencies (P10, P12, P14, P23, P26 and P32). Findings agree with Oesterreich and Teuteberg (2016) and discovered that cloud computing and BIM-based platforms could improve collaboration and communication if installed. It will enhance digital documentation and communication device with Internet access such as file-sharing, viewing platforms, distributing and collaborating on waste treatment in real time (P23, P27, and P31). Smart robotic bins, mobile digital dumpsites with semi-recycling applications and innovative pricing technologies emerged as the 4IR technologies that can play a significant role in mitigating the challenges facing the final disposal phase and reducing operational costs. Findings agree with Bruemmer (2016) and affirmed that automation of labour-intensive procedures such as robotics results in a decrease in costs. Concerning the challenges connected with the recycling phase, automation, cloud computing, mobile computing, social media, robotics, mobile semi-recycling plant and human–computer interaction emerge as the key technologies that can play a significant role to increase the efficiency of the households USWM if utilised in the management of waste. It agrees with Oesterreich and Teuteberg (2016) and discovered that 4IR technologies such as digitisation, automation and integration at all phases of value chain, BIM, cloud computing or the IoT, amongst others, can provide economic advantages for enhancing output, competence, excellence and partnership of the industry. For details of 4IR technologies’ role in mitigating the challenges associated with households’ USW, refer to Table 3 (Column 3).

6. Implication and benefit of this study

This paper promotes implementing 4IR technologies in USWM in Nigerian cities. It has far-reaching advantages to the residents’ well-being and their environment in general. Apart from the economic boost of the 4IR technologies, such as fast-tracking the phases from generation to recycling, the use of the 4IR technologies can mitigate the majority of the challenges facing USWM at various phases. Evidence shows that the combination of the

government and private agencies may not manage the geometric increase of the urban waste generated from households if not technologically managed. It implies that without digitalisation, their effort may be counter-productive. Thus, encouraging the use of 4IR technologies in conjunction with waste managers and other stakeholders like the residents to work together to resolve infrastructure development issues regarding the disposal and recycling to service standards and service charges may enhance greater performance in low-income cities across Nigeria. Examples of the 4IR technologies are automation, simulation model, mobile computing, cloud computing, BIM-based platform, GPS tracking system (human–computer interaction), IOT, smart robotic garbage bin, etc. These are elements of artificial intelligence and digitalisation (Wijenayake *et al.*, 2017). The authors affirmed that the smart robotic garbage bin could assist in mitigating challenges associated with improper garbage collection, house-to-house refuse collection and the use of neighbourhood bins. This mechanism has features such as IoT, human–machine interaction, bin space managing and smell control. Literature regarding USWM and the possible application of the 4IR technologies to proffer solutions to the majority of the challenges confronting Nigeria has been strangely quiet. This theoretical gap, amongst others, has been filled in the paper.

Regarding the practical contributions of the paper, these results will support and offer a better perspective into the challenges facing USWM and contribute to informing key stakeholders in the waste management sub-sector to create an enabling platform for implementing 4IR technologies in managing households USW in Nigerian cities. Also, the paper intends to stir up households USWM stakeholders concerning challenges influencing the management of solid waste from generation to recycling and the role of 4IR technologies in each phase as emerged and grouped. The engagement of the 4IR technologies in managing households USW can assist in improving economic and social inclusion via a transformation to a sustainable society. The positive relevance of the 4IR technology in any field has been recognised by international organisations such as the United Nations (United Nations News Centre, 2018). One of the outcomes will be the creation of an inhabitable environment. It will enhance the well-being of the residents and create sustainable clean cities across the country. The emerged recommendation from this paper is enlightening to the major stakeholders.

Regarding the benefits of this study to sustainable development and social work, this paper will reawaken the governments, waste administrators/managers and decision makers to re-examine the practice of 4IR as a mechanism to mitigate the challenges associated with USWM through simulation, robotic, artificial intelligence, radio-frequency identification, cyber-physical, etc. Therefore, mitigating the challenges influencing the management of USW is likely to curb social health issues through practical policies that will encourage 4IR technology application to manage waste from generation to recycling. Moreover, the world is matching towards the "Decade of Action (2030)," and key participants need to double their efforts to deliver regarding the SDGs (Ebekozien and Aigbavboa, 2021). The use of 4IR technologies on households USW can play an important role in this course. It is in line with the submission of Manda and Dhaou (2019) and affirmed that the 4IR technology could alleviate lack, climate alteration discrimination, joblessness, etc. These are parts of the issues being proffer feasible policies through the 17 SDGs. Implementing 4IR technology on households USWM can create economic prosperity to the ICT sector, reduce environmental degradation such as illegal dumpsites, mitigate social inequality across the cities and semi-cities and build stronger infrastructures such as recycling plants. These are elements of transformative change if magnificently executed via enabling policies and programmes.

7. Policy and recommendation

Evidence shows lax supervision of the USWM by the ministries or agencies in charge of public waste management across the cities covered. Inadequate funding, absence of an institutional framework and sustainable policy are the major hindrances to using the 4IR

technologies in managing USW across Nigeria's cities. The Nigerian Government economic plan attitude towards the 4IR policy and lax implementation may have stalled the technology practice in USWM. The waste management sub-sector is backward in this respect. Apart from mitigating the challenges affecting USWM, the technology can save time and cost in the long term, improve service delivery and collaboration, improve staff and environment safety, promote sustainable clean cities, etc. The study suggests that waste managing firms should be prepared to invest in the procurement of advanced digitalised technologies to manage USW. During the transformation stage (from the traditional system to the digitalised USWM), with a focus on sustainable and clean cities, collaboration with the government, residents and other stakeholders cannot be over-emphasised. It should be all-inclusive, including a high level of assurance from the political class and policymakers, to give direction for digital transformation and novelty in USWM.

The Nigerian Government at all levels (federal, state and local governments) should take the lead with feasible policies and laws that will promote the use of 4IR technology to manage USW. This policy should include access to finance or grant by registered and outstanding waste managing firms with unbeatable records to procure digital equipment. Also, the locations and management of dumpsites should be well defined. The host environment should be given first consideration. The day-to-day manpower to manage the digitalised equipment should be given the necessary training and re-training, including new employees of the USWM companies. The training and re-training will stir up flexible leadership and transformational learning skills in the staff. Technical issues regarding equipment such as the recycling plant should be well defined to suit our environmental laws. Thus, the efficacy and appropriateness of the technologies in a developing setting like Nigeria with the instability of electricity supply and local capacity to adequately maintain the equipment should be evaluated before importation. It is to avoid the "Cobra Effect" of a good intention.

8. Conclusion

This study highlights a collective perception of the challenges influencing households' USWM and the 4IR technologies's role in promoting sustainable developing cities across Nigeria. The paper discusses the five main challenges associated with each phase as identified (generation and separation; collection, transfer and transport; treatment; disposal; and recycling). This research contributes towards educating urban waste managers, NGOs in environmental and health matters, researchers and policymakers. The knowledge includes how technology such as automation, mobile computing, simulation, cloud computing, BIM-based platform, GPS tracking system (human–computer-interaction), IOT, smart robotic garbage bin, amongst others, could be used to manage USW. It would mitigate the challenges affecting the performance of USWM in Nigeria. Therefore, the results in this research should be considered as a first-stage assessment. It is because future analyses could be conducted on feasible issues around 4IR recommended for the households' USWM sector in other developing nations with the same characteristics as Nigeria.

This study can summarise some deductions to guide scholars, policymakers and urban waste managers regarding how 4IR technology role can mitigate the challenges facing USWM in Nigerian cities. There are some limitations to this study. First, the methodology (qualitative approach) adopted is an example. For future research, the study recommended a mixed-methods research design to achieve generalisability. Ebekozien *et al.* (2019b) adopted a similar suggested method. The authors affirmed that the essence is to enlarge the coverage and empirical results. Also, they demonstrated that the exploratory sequential, a type of mixed-methods research design, aids scholars in authorising the qualitative results. This research gap is lacking in the past published works regarding USWM and the role of 4IR. Second, crucial current and projected household USW data are needed to identify the suitable

investment in digital technology across Nigerian cities. From a practice viewpoint, the developed framework should be further tested in other developing nations with similar USWM and ICT background characteristics.

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Appendix

Oral interview questions

Dear Participant,

Request for Interview

In less than a decade to Sustainable Development Goals, the urban solid waste (USW) emanating from households, especially in developing countries, calls for concern. Several policies have been suggested and some implemented, but the challenges facing USW management remain. Fourth industrial revolution (4IR) technologies have been proved successful in improving urban public services. The role of 4IR technologies in mitigating the challenges of USW is yet to receive in-depth studies in Nigeria. Therefore, this research is titled: **Urban Solid Waste Challenges and Opportunities to Promote Sustainable Developing Cities Through the Fourth Industrial Revolution Technologies.** Specifically, the researchers will achieve the aim through the following objectives:

(1) To examine the challenges facing households' USWM in developing cities across Nigeria.

(2) To explore the role of 4IR technologies in mitigating the challenges facing households' solid waste management in developing cities.

Please note, questions for the virtual interview are going to be within the paper's stated objectives. Responses provided by you will be collated and analysed together with that of other interviewees. It will make up the findings, and all information provided will be handled with the greatest secrecy.

Hence, your valuable time and other input in answering the questions and contributions will be highly cherished.

Kind regards.

Yours faithfully,

(Research Coordinator).

Basic questions for the participants

(1) Please, for record purposes, what is the name of your organisation? (If necessary).

(2) Please, what is your position in this organisation, and how long have you been working?

(3) Please, are you knowledgeable regarding the fourth industrial revolution (4IR) or Industry 4.0?

(4) Please, do you know how 4IR can be used to manage urban households waste?

(5) In general terms, from your perception, how can you describe the increase in household waste emanating from urban locations across Nigerian cities?

(6) Do you think there are challenges facing households' USWM in developing cities across Nigeria?

(7) If yes, can you identify and discuss more on them?

(8) Do you think the government has created an enabling environment for private waste managers to be involved in solid waste management in your locality?

(9) If yes, can you explain?

(10) If no, is there a likely reason(s)?

(11) Do you think the 4IR technologies can mitigate some of these challenges?

(12) If yes, please, can you explain?

(13) Please, from your experience, can you identify the technologies you know in connection with the 4IR that can be of benefit to mitigate some of the challenges facing urban household solid waste management?

(14) As a stakeholder in the sector, are you satisfied with the equipment used to manage solid waste regarding the 4IR technologies?

(15) If not, please, what do you think are the issues affecting the use of 4IR technologies on USWM?

(16) What role do you think the government can play to support and create the enabling environment to build more resilient, healthy cities across the country via 4IR technologies?

(17) What are the feasible policies to support and create the enabling environment to build a more resilient healthy cities across the country via 4IR technologies?

(18) Do you think 4IR technology usage in managing USW can be used to achieve sustainable development goals regarding clean cities and a healthy environment before the year 2030 in Nigerian cities?

(19) If yes, please, how can this be achieved?

(20) If not, why do you think so?

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