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Review

Critical Infrastructures: Reliability, Resilience and Wastage

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Abstract: By 2050, according to the UN medium forecast, 68.6% of the world's population will live in cities. This growth will place a strain on critical infrastructure distribution networks, which already operate in a state that is complex and intertwined within society. In order to create a sustainable society, there needs to be a change in both societal behaviours (for example, reducing water, energy or food waste activities) and future use of smart technologies. The main challenges are that there is a limited aggregated understanding of current waste behaviours within critical infrastructure ecosystems, and a lack of technological solutions to address this. Therefore, this article reflects on theoretical and applied works concerning waste behaviours, the reliability/availability and resilience of critical infrastructures, and the use of advanced technologies for reducing waste. Articles in the Scopus digital library are considered in the investigation, with 51 papers selected by means of a systematic literature review, from which 38 strains, 86 barriers and 87 needs are identified, along with 60 methods of analysis. The focus of the work is primarily on behaviours, barriers and needs that create an excess or wastage.

Keywords: critical infrastructure; strain; waste behaviour

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1. Introduction

The notion of the critical infrastructure is well-documented (with a full classification provided by the United States Department of Homeland Security in [1]). Society relies on the critical infrastructure service provision, and their interconnectivity is immensely complex providing an ever-growing research trend within domains such as cyber [2], resilience [3,4], physical protection [5] and cascading failure modelling [6]. Alongside these mainstay research areas, as this article demonstrates, critical infrastructure strain is receiving growing attention. This is because over half of the human population is predicted to live in an urban environment in the near future [7,8], exacting considerable demand on existing critical infrastructure distribution channels and their interdependence that could result in severe shortcomings during periods of high demand. For instance, Sänger et al. [9] discuss the effect COVID-19 had on existing healthcare infrastructures and Chan et al. [10] outline the transport strains of moving huge amounts of passengers and freight on railway under extreme environmental conditions. A further example is discussed by Mlambo [11], who documented a crisis looming over South Africa for future water distribution networks, where the water deficiencies are multifaceted, with climate change, water theft and a lack of infrastructure investment (for example, new dams, old pipe networks) to match the urbanisation growth as two core contributors [12,13]. The climate change issue of course adds further complications to the strain caused by urbanisation and extends beyond South Africa, as Páez-Curtidor et al. [14] discuss in their work on climate-resilient water safety plans for India.

Going forwards, a synergy should be established between (i) upgraded infrastructure and (ii) a reduction in waste behaviours (i.e, excess) to cater for strain and the future demands placed by urbanisation. Relating to point (i), suitable technologies discussed in the literature include integrating AI/machine learning techniques [15], IoT sensors [16], digital twinning technologies [17,18], smart grid [19] and solar and wind [20]. Regarding point (ii), as discussed later in the findings, a suitable approach for eliminating waste-generating behaviour is through education and developing an awareness of the impact waste behaviour has on the availability of critical services. However, the aim of this article is to further the discussion on point (ii). To achieve this, a systematic literature review (SLR) methodology is adopted focusing on articles over a 5-year period from November 2017 to November 2021.

To date, other SLR investigations have been conducted in critical infrastructure-related domains. For example, Couto et al. [21] conducted a review on the water, waste, energy and food nexus, focusing on Brazil. Their article emphasises critical interlinkages neglected in the literature, factoring in the synergies between natural resources. Sänger et al. [9] investigated critical health infrastructure resilience, focusing primarily on water supply. Guo et al. [4] focus on resilience under disasters and disruptive events, and Chowdhury [22] focuses on cyber-security specifically for nuclear power plants. However, the research in this article stands apart from other works by focusing on human-based waste behaviours within the critical infrastructure domain, where limited work has been conducted. To form the investigation, the following four research questions (RQ) are considered: (RQ1) which critical infrastructure domains are focused on primarily for waste reduction? (RQ2) Do articles tend to involve participants in the investigation? (RQ3) What are the main barriers or needs and the resulting strains on critical infrastructures? (RQ4) What methodologies are typically employed for the investigations? The SLR approach adopted in this article is an adaptation of the work by Tummers et al. [23], originally modelled on the work by Kitchenham [24]. Within existing SLR reviews, the duration of the paper search period varies. For example, Chowdhury [22] considers works from the last 10 years, whereas Sänger et al. [9] include articles from the last 30. In [25,26], the authors consider articles from the last 5 years, and this is a process we have also adopted in this investigation. Prominent in the search is the term waste, which refers to 'excess' in this article rather than sewage/trash.

The rest of the paper is as follows. Section 2 outlines the methodology for the SLR. Results are discussed in Section 3 along with a discourse on the findings. The conclusion is provided in Section 4.

2. Materials and Methods

The SLR methodology adopted focuses on a query-based search in the Scopus digital library using a compilation of the keywords outlined in Table 1.

Table 1. Keywords and Search Query.

Keywords	Query String
Waste/Wastage Behaviour/Behavior Critical Infrastructure Infrastructure	Title-ABS-Key ((“waste” OR “wastage”) AND (“behaviour” OR “behavior”) AND (“critical infrastructure” OR “Infrastructure”)) AND (Limit-To (DOC-TYPE,”ar”)) AND (Limit-To (PubYear,2022:2017))

2.1. Search Strategy

In this investigation, a 5-year timeframe is considered to be appropriate due to the fast-moving pace of information technology, and this also aligns to other SLR works such as [27]. Table 1 details the list of keywords and a conceptual search query used for the Scopus-based article output. The selection of keywords is based on adopting a novel approach for the investigation. As defined in the Introduction, other SLR works tend to focus on synergies between natural resources [21], disaster management [4] or cyber-security [22]. However, at the time of writing this article, SLRs on waste behaviours within the critical infrastructure domain are lacking. In addition to the query-based search, 11 further articles were found after snowballing (for example, the article by de Bruyn et al. [28], which is linked to this Special Issue paper), of which, 4 were later removed following examination of the article contents and quality analysis process. Four selection criteria (presented in Table 2), involving questions considered in [23], were employed to reduce the initial article count from 375 to a final amount of 55 prior to the Quality Analysis (QA). SQ1 to SQ3 were automated during the filtering process on the Scopus digital library. SQ4 and SQ5 were performed by hand by reading the full title, abstract and keywords.

Table 2. Keywords and Search Query Prior to QA.

Label	Selection Criteria	Count
SQ1	Full Search String	364
SQ2	Written in English and from the last 5 years	314
SQ3	Full Journal Article	209
SQ4	Relates to critical infrastructures, thus validating the current study	63
SQ5	Article Availability	55

For SQ4, some articles aligned well (in principle) to the search query, but the focus was on waste management, i.e., sewage logistics, rather than waste behaviours, or activities/patterns resulting in waste, excessive production or unsustainable practice in critical infrastructures. This is logical, and a result of the duel meaning of the word 'waste', which is used in literature to cover both studies on sewage and litter (trash), as well as the term excess that is related to this study. Therefore, removal of waste management papers required manual filtering, such as the work discussed by Thiel et al., that discussed personal protective equipment (PPE) waste build up [29], demolition waste as in [30] or discussion of waste reduction through second life cycle as in [31]. Filtered works also included discussion of COVID-19 in waste samples as in [32].

However, in the work by Sandhu et al., the focus is on throw-away coffee cups, yet the article is included as it is related to consumer behaviour with regard to eco-friendly choices [33] and relates to waste management as a critical infrastructure. Crucial in the selected papers is that human behaviour is involved in the application and that the work relates to one (or multiple) critical infrastructure types. For example, Wang et al. discuss environmental waste, but the focus is on incentivising humans to act [34]. Regarding SQ5, in some cases, articles required an institutional licence or subscription fee. Where possible, the authors requested articles through ResearchGate that were unavailable due to payment restrictions on the digital source (if no response was provided after 10 working days, the article was removed from the SLR).

2.2. Quality Assessment

The QA is a manual procedure involving reading each article and scoring by the quality criteria (either 1, 0.5 or 0, with 1 referring to the highest and 0 the lowest) as detailed in Table 3.

Table 3. Quality Assessment.

Label	Selection Criteria
QA1	The aims are clearly stated
QA2	Scope, context, experimental design clearly stated
QA3	Research process documented adequately
QA4	Journal Ranking
QA5	Coupled with real-life application (i.e., applied)
QA6	Direct link to the research focus of the study (i.e., clear reference to strain)

Points are assigned to the article for a clear outline of the aims (QA1); clear definition of the scope, context and experimental design (QA2); thorough documentation of the research process (QA3); the journal ranking, where Q1-Q2 journals are given a score of 1, Q3-Q4 journals are graded as 0.5 and unranked journals are graded as 0 (QA4); if the work is coupled to a real-life application (rather than the purely theoretical) (QA5); and if there is a direct link to the research focus of the study (i.e., clear reference to strain) (QA6). The final scores should not be considered a full reflection of the article quality (as many are published in Q1 journals), but rather the suitability to align with this study. The highest score an article could receive is 6, with the lowest possible score being 0. An overview of the article filtering process is presented in Figure 1, with an indication of the QA score distribution presented in Figure 2.

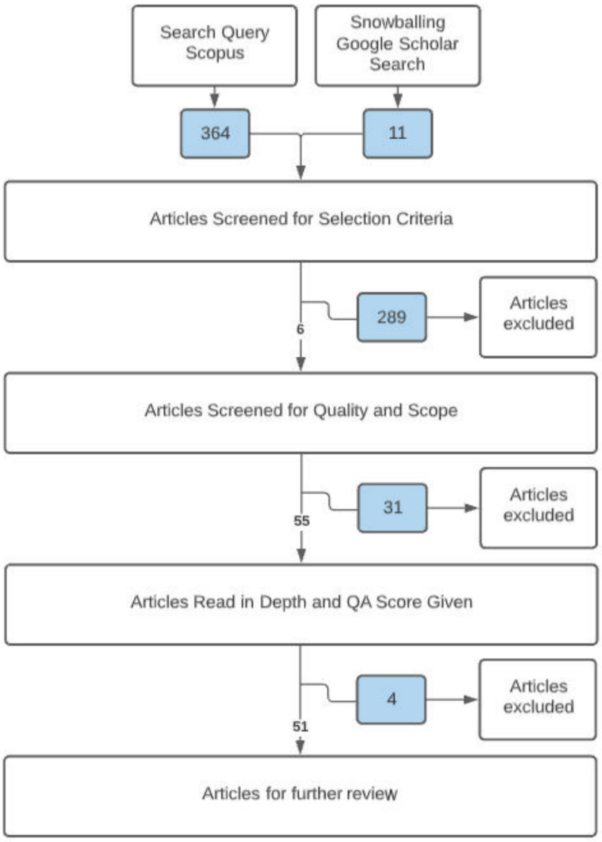

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Diagram.

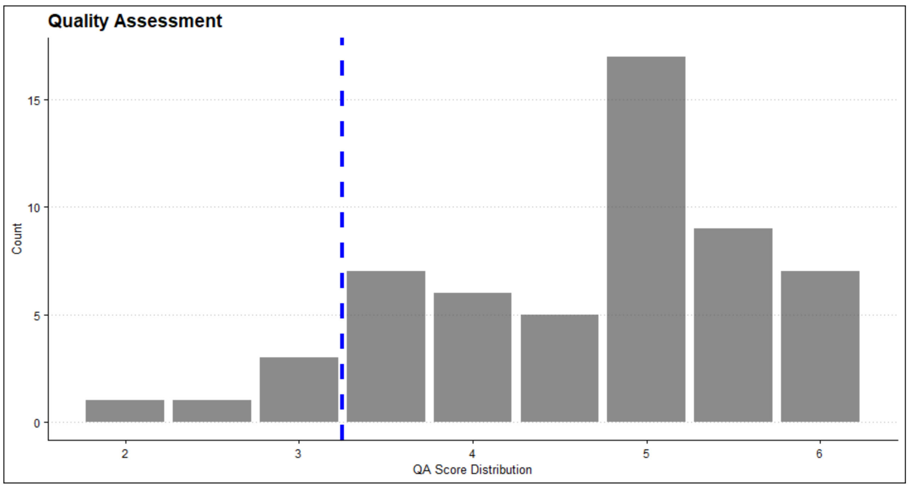

Figure 2. Quality Assessment Scores Overview.

2.3. Data Extraction

Data extracted from each article involved reading through the full contents and completing a form (provided in Table 4) for all. Overall, from the 51 articles, 73 strains are identified, along with 105 barriers and 129 needs in the investigations. These values are then reduced by use of the selection of categories derived through the identification of common themes and the removal of duplicates (and generic terms), resulting in a final count of 38 strains, 86 barriers and 87 needs. Furthermore, the articles discussed 9 of the 16 critical infrastructure domains (with some articles covering multiple domains), and in total there were 18,663 collated participants surveyed across the 51 articles.

Table 4. Data extraction sample.

Label	Data Extraction Sample
Article ID	8
Keywords	High resolution energy consumption data
Needs	Consumer-specific demand response initiatives
Barriers	Forecasting in residential buildings
CI-Domain	Energy
Behaviours	Consumer demand
Strains	Energy waste
Survey	96
Limitations	Short-term electric consumption
Models	K-means

3. Results

In this section, an overview of the articles involved in the SLR process is provided, followed by a response to the research questions outlined in Section 1.

3.1. Overview

The majority of the articles found in the SLR (and snowballing) approach were open access. Figure 3 details and overview of the count relating to the final 51 articles involved in the investigation, with Table 5 and Figure 4 providing a breakdown of the articles by year. Figure 4 suggests a growing trend in this investigation domain over the five-year period, where the SLR 2021 has more than double the representation of articles than 2018.

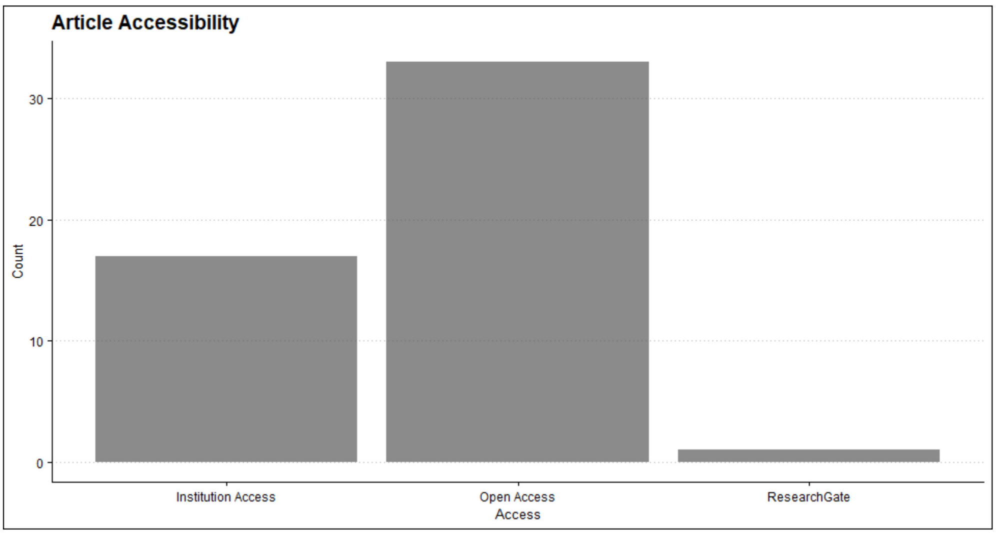

Figure 3. Article Accessibility.

Table 5. Primary Studies Following the QA Process Organised by Year.

Year	Articles
2017	[35–37]
2018	[38–47]
2019	[48–53]
2020	[8,54–63]
2021	[28,33,64–82]

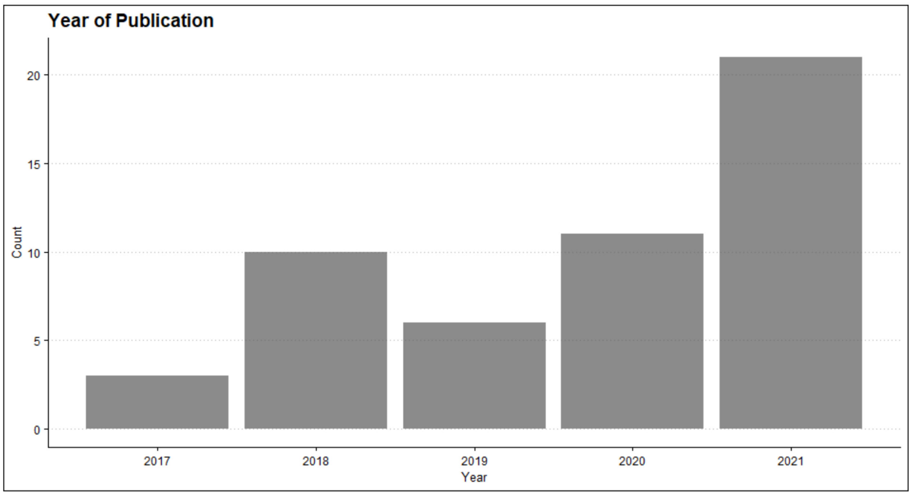

Figure 4. Year-wise Distribution of the Studies.

In the following sub-sections, the research questions outlined in Section 1 are addressed by means of a discussion into recurring trends, critical infrastructure domains, needs, barriers, strains and models identified in the SLR.

3.2. (RQ1) Which Critial Infrastructure Domains Are Focused on Primarily?

The 16 critical infrastructure sectors outlined in [1] are presented in Table 6. Within the SLR investigation, 9 critical infrastructure types were investigated. They include Energy, Food, Healthcare, ICT, Telecom, Transport, Waste and Water. Whilst not part of the critical infrastructure classification in [1], homes (that is, residential properties) are also included in the investigation, as other works (for example, [83,84]) discuss the interlinkage of residential properties with critical infrastructures and, therefore, they form part of the discussion.

Table 6. Sixteen Widely Acknowledged Critical Infrastructure Sectors.

Critical Infrastructure Types			
Chemical Sector	**Dams**	**Finance**	**Information Technology**
Commercial facilities	Defence industrial based sector	Food and agriculture	Nuclear reactors (and materials and waste)
Communications	Emergency services	Government facilities	Transportation systems
Critical manufacturing	Energy	Healthcare	Water and wastewater

As Figure 5 depicts, waste (27), energy (17), food (13) and water (8) are dominant trends within the studies. The lowest representation was ICT, Telecom and Homes with one article each. For example, within the energy domain, Bostenaru Dan et al. [79] discuss thermal power plants in rural areas, and Pulselli et al. [40] discuss energy transition for decarbonising urban neighbourhoods; both authors relate to single specific geographic locations (Romania and Seville, respectively) as a reference for their research into sustainability within the energy domain. Within the waste category, examples of literature include Salem et al. [61], who focus on waste management in one specific geographical location (Gaza Strip), Massoud et al. [73], on waste management practices in low-middle income countries, and Subiza-Pérez et al. [57], who focus on social acceptance of municipal waste incineration plans. Within the food and water domains, examples include the work by Babbitt et al. [68], who investigate residential food provisioning (specifically during the COVID-19 pandemic), and Prouty et al., [58] who focus on water networks and the implications of extreme weather events on the service provision and infrastructure.

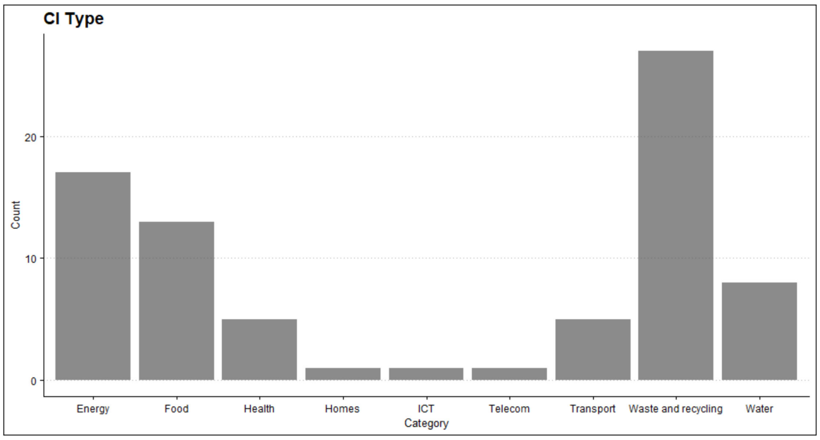

Figure 5. Critical Infrastructure Domains in SLR.

Furthermore, it should be noted that some articles have a duel classification, for example, Kibler et al. [41] investigate Food, Water and Energy, Chung et al. [50] cover both Waste and Health, Maase et al. cover Energy and Transport [43], and Shoukourian et al. [59] focus on both ICT and Energy. Appendix A Table A1 provides an overview of the critical infrastructure domain by author in alphabetical order.

3.3. (RQ2) Do Articles Tend to Involve Participants in the Investigation?

In total, the studies involved 18,336 participants. With the highest level of survey participants in the work by Pulselli et al. [40] on energy transition, with 5364 in total. There were some low participation studies, for example, in the work by Gokarn et al. [35], seven participants were surveyed, but the results were validated by expert panels. This is a similar approach to Chen et al. [80], who surveyed 428 participants and validated the findings by means of 10 experts. Kamble et al. [52] involved 12 participants in the survey but employed a literature search to validate the findings.

Overall, 36 articles involved participants (3 of which did not state the surveyed number) and 15 articles did not involve surveys/participants in the investigation. An overview of the participants per critical infrastructure domain is visualised in Figure 6. Where articles cover multiple domains, the overarching domain type is employed in the graphic (meaning the categories diverge from those presented in Figure 5). The *x*-axis depicts the survey participants, while the domain types are highlighted on the *y*-axis.

3.4. (RQ3) What Are the Main Barriers or Needs and the Resulting Strains?

Coelho et al. [44] discuss several needs within the energy sector, for instance, energy-cost saving, efficiency measures, renewable production (at all levels with a local emphasis) or targets for climate actions. These are common traits within other articles in different domains. For example, Barreiro et al. [8] discuss climate action within the urban resilience domain, Deng et al. [66] within the water domain and Ichikoitz et al. [54] within the waste and recycling domain (specifically highlighting the growing volume of e-waste in South Africa). Furthermore, Ichikoitz et al. [54] also discuss climate-related needs. Other notable points include protection of infrastructures from weather in [58], consumer participation in food waste management in [68] and the need for greater education programs for supporting customers with purchases to reduce waste and on waste-sorting programs to reduce the strain on landfill or collection networks [33,48,49].

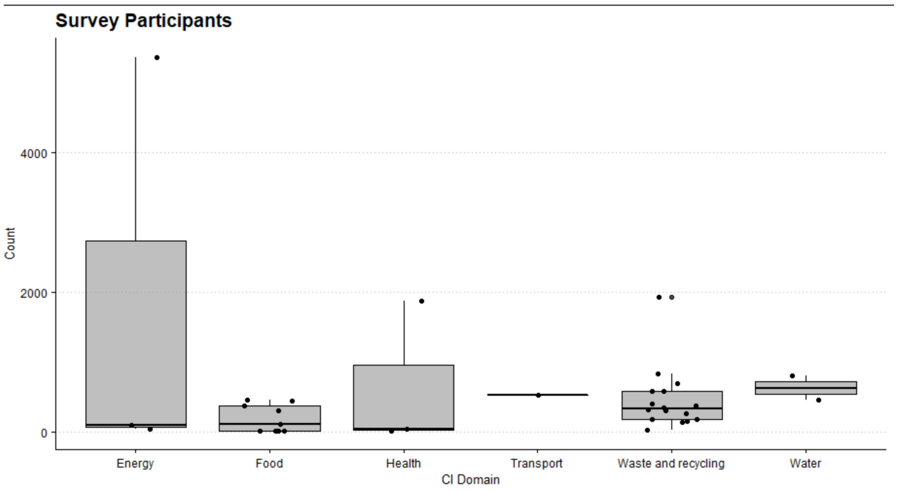

Figure 6. Survey Participants by Critical Infrastructure Domain.

There is bias in the needs associated with Transport, as only one article in the SLR focused implicitly on transport, in which taxi routes within aviation are discussed. However, articles from other critical infrastructure domains also discussed transport issues, for example Chen et al. [80], who refer to the needs for greater use of local resources to support transport networks. The overall findings from the SLR related to the identified needs are presented in Appendix A Table A2, with a sample of the findings in Table 7.

Table 7. Identified needs from overall findings.

Ecology and Health	Policy	ICT	Transport	Education	Socio-Economic	Infrastructure
Environmental protection	Enforce regulations	BIM approach	Allocate taxi routes to aircraft	Campaigns/Training Programs	Adverse social reactions	Protection from extreme events
Sustainable decisions	Company collaboration	Capture complex system dynamics	Robust taxi time	Education in making purchases and reducing waste	Consumer participation in food waste management	Ease of access to recycling bins
Greening industrial waste	Dedicated team (for monitoring and co-ordinating local authorities)	Highly dependent on accurate utilization data	Transportation	Decrease the perceived cost of rural people	Consumer-specific demand response initiatives	Effective use of limited available resources
Landscape as a proactive eco-systemic infrastructure	Banning food from landfill	Lack of studies on IoT adoption in food	Use of local resources	Educational interventions	Improve the perceived benefit	Government provision of more infrastructure
Reduce greenhouse emissions	Dynamic strategic adjustments	New Technology	Reduce the distribution distances	Greater investment in education	Respondents were more willing to buy a product if it was recyclable	Improved efficiency of industrial processes and equipment

Regarding the barriers discussed in the 51 articles (of which, Table 8 presents a sample—with the full list of barriers in Appendix A Table A3), the categories of Ecology and Health (16), Policy (16), ICT (16) and Socio-Economic (19) had almost equally prominent representation, with a similar number of barriers identified for Infrastructure (12). Much of the ICT barriers were related to articles discussing the issues surrounding IoT (integration, governance, cost, compatibility, etc.), for example in the work by Kamble et al. [52], where a comprehensive list is provided on the barriers relating to IoT implementation. Regarding Ecology and Health, COVID-19 was discussed in [74,77,79], with other topics such as the pervasiveness of takeaway culture in [33] and other people-driven behaviours relating to the proper sorting and separation of waste [72] causing strain on landfill and collection networks. Uncertainty over weather patterns [56] and climate change [44,54] were also listed as barriers.

Table 8. Sample list of barriers.

Ecology and Health	Policy	ICT	Transport	Education	Socio-Economic	Infrastructure
Pervasiveness of takeaway culture	Focus on individual country	Suspension on deployment of new data centres	Inadequate vehicle routing	Classification knowledges for WCI	Low participation rate in waste separation (17%)	Sustainable supply
Food characteristics	Inefficiencies in planting, harvesting and water use	Adoption of IoT is still in its nascent stage	Uncertainty in other transportation problems	Pharmaceutical products consumed and disposed	Growing urban populations	Many low and middle-income countries
Infectious agent may be of zoonotic rather than human	Garbage classification	Exploiting big data sources	Geographical access	Consumers' awareness	Densely populated regions	Urbanisation
High export percentage of circuit boards and plastics recycling	Policy instruments on perceived value	Streamlined communications	Insufficient funds		Attitude to waste disposal	Infrastructure to harness data
COVID-19	Relies on voluntary waste diversion strategies	Lack of government regulations for IoT			Public vs. private sector participation	Imperfect and lack of infrastructure

The full list of strains identified in the 51 articles is presented in Table 9 below. The dominant categories of strains were within Ecology and Health, Socio-Economic and Infrastructure. In total, 10 articles discuss carbon emissions, with a further 10 discussing landfill/trash and the environment in general. For example, Ichikowitz et al. [54] discuss the strain caused by e-waste, and [64–66] are examples of works discussing the straining impact on the environment. Six articles discuss energy burdens, for instance, Khahro et al. [81] discuss the benefits of Building Information Models (BIM) in this domain, and Xu et al. [47] discuss waste heat recovery in power plants. Regarding further discussions on Infrastructure, strains include growing tourism [39], management at landfill sites [48], water waste [69] and increased production [56].

Table 9. Strains identified from articles.

Ecology and Health	Policy	ICT	Transport	Socio-Economic	Infrastructure
Pollution (plastic/water) Sustainability Climate change e-Waste Waste volume Environmental footprint Dumping and burning Carbon emissions Environmental health Health strain Food waste Waste entering landfills Environ. Contamination Water consumption	Political pressure Waste management	Energy burden	Food networks	Food purchase Food production Food security Informal settlements Garbage siege Collaboration	Supply of water Lack of space Water waste Management at landfill Increased production Growing tourism Urbanizing water cycle Waste management Energy consumption Energy waste Energy Efficiency Fuel Supply Variability

Informal settlements are outlined as a strain in [53], with garbage siege identified as a strain in [76]. Strains relating to food (production, purchase and security) are also discussed in [55]. Documentation of the strains related to Policy, ICT and Transport were somewhat limited compared to their prominence in the discussion on needs and barriers. However, Schmitt et al. [70] outline the transport strain on food networks, and Shoukourian et al. [59] outline the energy burden in the ICT domain.

In summary, Figure 7 displays a count-based comparison plot of the strains, barriers and needs within the 51 articles.

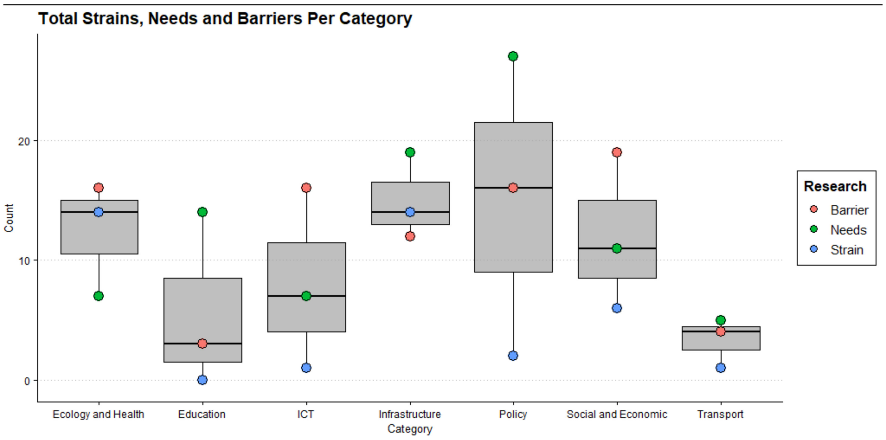

Figure 7. Count-based comparison plot of strains, barriers and needs.

3.5. (RQ4) What Methods of Analysis Are Typically Employed for the Investigations?

In total, 81 methods of analysis are used within the 51 articles. As with the needs, barriers and strains, duplicates are removed, resulting in a final identification of 60 approaches, as listed in Table 10. Many could be categorised under statistical analysis (for example, ANOVA [82], Chi-square [68], Pearson correlation [54], *t*-test [82], Wilcoxon–Mann–Whitney rank-sum test [37], and Welch [50], etc.). Other categories could include machine learning (k-means [65], and Logistic regression [72], etc.), deep learning (Artificial Neural Network [42]) and model-based (for example, causal loop diagrams [58], agent-based [62]).

In summary, the dominant approach is to adopt a statistical analysis for the evaluation. This would align with the high number of articles involving human-participants in the investigation. Articles also involved simulation, for example, [38,45] accounting for the use of causal-loop diagrams and agent-based modelling investigations.

Table 10. Methods of Analysis in Alphabetical Order.

List of All Methods of Analysis Identified (Alphabetical Ordering)					
Convenience Sampling Means	Causal Loop Diagrams	Fuzzy Delphi Method	integrative Analytical Framework	Multiagent Decision-Making Functions	Randomized Controlled Trials
Cognitive best-worst method	CD's iterative and user-focused approach	Fuzzy inference	Interpretive Structural Modelling	multi-level perspective	Reactive transport models
Agent based model	Chi-square	Fuzzy Logic Forecasting	ISM and DEMATEL methodology	Multiple regression analysis	Schultz's intervention model
Analysis of variance	Cronbach's alpha	Game Payment Function	k-means	multisectoral and cross-functional method	Simple Random Sampling
ANOVA	Composite reliability indices	Gated Recurrent Unit (GRU)	Kruskal–Wallis tests	Multisubject interaction	Statistical methods of One-way analysis of variance
Artificial Neural Network	deep learning	Guilford's interpretation of the magnitude of r	Logistic regressions	partial least squares structural equation modeling	Structural equation model (SEM)
Average Index	Descriptive statistics	Hidden Markov Model	Long Short-Term Memory Unit (LSTM)	Pearson correlation	thematic content analysis
Building Information Modelling	Exploratory Factor Analysis	hierarchical linear regression	Mamdani fuzzy rule-based system (FRBS)	Principal Component Analysis	*T*-test
Carbon accounting method	F2f interview	holistic resilience assessment methodology	MICMAC analysis	Probability Proportional to Size sampling	Welch
Causal loop	Flow diagrams	IDAF framework, Long Short-Term Memory (LSTM)	Model of justified behaviours (MJB)	Quickest Path Problem with Time Windows (QPPTW)	Wilcoxon-Mann–Whitney rank-sum test

3.6. Discussion

Finally, discussion is provided on behaviours present in the 51 articles in this section. As previously outlined, 18,336 participants were surveyed in 36 of the 51 articles. This provided ample insight into waste behaviour traits that others can build on. For example, a common theme within a portion of the articles relates to consumer behaviour with regard to the classification of rubbish, and the resulting strain this causes on the environment, landfill management and collection networks. As solutions, educational practice is proposed as a way forward to mitigate the resulting 'garbage siege' [76] caused by urbanisation. However, poor garbage management behaviours were present outside of residential properties, with Mensah [78] discussing that fisherfolk (in Ghana) have a low level of waste sorting and are unwilling to pay for collection services.

Other behaviour points identified include sustainable consumption, relating to material goods, energy, food and water. As such, González-Briones et al. [42] discuss the benefits a policy driver could play in this domain to reduce food waste and encourage investment in infrastructure. However, the emphasis of many articles is on better educational practice, information sharing, awareness [53], more customer involvement in decision making and better support and policies driven by local authorities. However, in some instances, health is also a cause of behavioural patterns, for instance the wastage behaviour caused by COVID-19 stockpiling [68]. Environmental issues are also a driver for change, not just for residences, but also commercially. Culture, social-expectations, shopping habits and attitudes were also drivers relating to wasteful behaviours that are damaging to the environment, as discussed in [39].

In summary, there were some limitations within the investigation, for example articles which would have been useful for the investigation were omitted due to their unavailability online or restricted payment. Furthermore, 10 articles were requested via ResearchGate, but no response was received after 10 working days. It was also clear that the search string could be strengthened as the snowballing (hand-search) accounted for missing articles. Future approaches could include other search strings incorporating different critical infrastructure types as keywords.

3.7. Going Forward

Within the critical infrastructure domain, it is crucial to develop solutions to support strains through integration of ICT technologies. The approach employed in this paper has recognised limitations, particularly regarding the implementation of IoT [52], cost barriers and infrastructure barriers addressed. Nonetheless, there are clear benefits; for instance, use of machine learning and deep learning techniques that can support preventative maintenance solutions for better infrastructure management. Work in this area is already being conducted within the manufacturing industry, where machine learning is combined with digital twinning technologies to predict and detect failures within the production chain. The full potential of digital twins is yet to be explored, however, the digital twin market exceeded USD 4 billion in 2019 and is predicted to grow by a further 30% by 2026. There is a clear scope for an application of this technology for supporting critical infrastructure management practices.

Water waste is a common problem globally as demonstrated in the broad range of article sources present in this investigation. In addition to including serious mechanical faults (for example, pipes left broken, valves/pumps malfunctioning), water waste also refers to simple home behaviours which cause high levels of excess use (for example, leaving the shower on to warm up before using the water, using half-filled dishwashers and over-use of garden sprinklers). Little research has been conducted into the behavioural profiling of water waste behaviours, and this investigation recognises that it is a core challenge for creating sustainable water resources for the future.

The need to understand the water governance process, in particular, is highly beneficial for society as power, food, health and supply networks rely on this infrastructure [58]. Water deficiencies also have a wide-ranging detrimental impact on the rural areas. With rural areas being prime sources of food provisioning for the nation as a whole, effective water governance is paramount. In addition to the availability of water, water quality is also under stress, for example, by extreme weather changes that are globally increasing in occurrence and severity due to global warming.

Focusing on resource efficiency is most appropriate, given the challenge of the project (that is, rising urbanisation and reducing water resources). A well-known example of resource efficiency is within the precision farming domain, where digital twin technologies are being used with high success for producing higher crop yield. The techniques used offer key value for resource efficiency, with tremendous benefits for a cheaper and higher crop yield (for example, reduced pesticide/fertiliser/water, increased use of marginalised land, reduced pest damage hence higher market value, lower drought damage). Yet, the approach is only possible with a detailed understanding of the holistic crop management process, supporting a reduction of strains on food production.

4. Conclusions and Future Work

In this article, the needs, barriers, strains, behaviours and methods of investigation relating to critical infrastructures were investigated by means of an SLR using the Scopus digital library. From an initial search result of 364 articles, 51 were selected for review following the selection criteria and quality assessment process. Key findings are outlined by discussing four research questions in Sections 3.2–3.5: (RQ1) which critical infrastructure domains are focused on primarily? (RQ2) Do articles tend to involve participants in the investigation? (RQ3) What are the main barriers or needs and the resulting strains? (RQ4) What models are typically employed for the investigations? Reflections on the findings and subsequent discussion provided in Sections 3.6 and 3.7 lead the authors to consider possible approaches for overcoming the barriers identified. Namely processes and further research into the standardisation (and optimal regulation) for the deployment of IoT would better facilitate automation that would result in a reduction in waste and higher level of resilience for critical infrastructures. Education and streamlined communication are also crucial for overcoming several barriers, not only in terms of skills training on IoT technologies, but also for a greater general public awareness on waste volume, waste attitudes and behaviours and the impact the micro level has on a macro scale.

Limitations of this work relate to the search string, meaning future directions for the work include expanding the search query by incorporating other related terms, such as sustainability, modelling, etc. Furthermore, some of the 16 critical infrastructure domains identified in [1] are under-represented in this search (for example, Transport and ICT) as, amongst the 51 articles, only 9 discussed these domains. Possible future directions for the study could, therefore, also include investigations into the under-represented critical infrastructure domains in this article by incorporating grey literature into the findings.

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Appendix A

Table A1. Critical Infrastructure Domain by Author.

Author	Critical Infrastructure Domain
Degenstein [64]	Waste and Recycling
Sidhu [65]	Waste and Recycling

Table A1. *Cont.*

Author	Critical Infrastructure Domain
Brownlee [38]	Transport
de Bruyn [28]	Energy
Deng [66]	Water and Energy
Khan [67]	Energy
Gokarn [35]	Food
Barreiro [8]	Water, Energy, Transport, Waste, Telecom, Environment
Babbitt [68]	Food and Health
Jamal [48]	Waste and Recycling
Ee [39]	Food
Ichikowitz [54]	Waste and Recycling
Karadagli [69]	Water and Wastewater
Schmitt [70]	Food and Health
Gausa [55]	Food
Perakis [56]	Food
Zhang [71]	Waste and Recycling
Heydari [72]	Waste and Recycling
Massoud [73]	Waste and Recycling
Zheng [74]	Waste and Recycling
Pulselli [40]	Energy
Sandhu [33]	Waste and Recycling
Subiza-Pérez [57]	Waste and Recycling
Končar [75]	Transport
Prouty	Water
Peng [76]	Recycling
Burton [77]	Water
Mensah [78]	Waste and Recycling, Food, Health
Kibler [41]	Food, Water, Energy
Shoukourian [59]	ICT, Energy
Bostenaru Dan [79]	Energy
González-Briones [42]	Energy
Chen [80]	Food
Morone [49]	Food
Chung [50]	Health, Waste and Recycling
Amirudin [51]	Food, Waste and Recycling
Niles [60]	Waste and Recycling
Kamble [52]	Food
Khahro [81]	Energy
Sinthumule	Waste and Recycling
Maase [43]	Energy, Transport
AlHaj [82]	Waste and Recycling
Salem [61]	Waste and Recycling
Hansmann [36]	Waste and Recycling
Allen [62]	Homes
Coelho [44]	Energy
Gao [45]	Energy
Barnes [46]	Water
Ma [63]	Waste and Recycling
Geislar [37]	Food
Xu [47]	Energy

Table A2. Full List of Identified Needs.

Ecology and Health	Policy	ICT	Transport	Education	Socio-Economic	Infrastructure
Environmental protection	Enforce regulations	BIM approach	Allocate taxi routes to aircraft	Campaigns/Training Programs	Adverse social reactions	Protection from extreme events
Sustainable decisions	Company collaboration	Capture complex system dynamics	Robust taxi time	Education in making purchases and reducing waste	Consumer participation in food waste management	Ease of access to recycling bins
Greening industrial waste	Dedicated team (for monitoring and co-ordinating local authorities)	Highly dependent on accurate utilization data	Transportation	Decrease the perceived cost of rural people	Consumer-specific demand response initiatives	Effective use of limited available resources
Landscape as a proactive eco-systemic infrastructure	Banning food from landfill	Lack of studies on IoT adoption in food	Use of local resources	Educational interventions	Improve the perceived benefit	Government provision of more infrastructure
Reduce greenhouse emissions	Dynamic strategic adjustments	New Technology	Reduce the distribution distances	Greater investment in education	Respondents were more willing to buy a product if it was recyclable	Improved efficiency of industrial processes and equipment
Source segregation of food waste	Effective policy drivers	Pairing social and technical innovations		Importance of information	Take into account public perceptions	Infrastructure to strengthen the intention-behaviour conversion
	Efficient collection of plastic waste	Weight sensors to measure the bin levels		Increase citizens' awareness and responsibility toward solid waste source separation	Urbanisation (in 2050, 68% of the population will be living in cities)	More convenient and sustainable options for clothing disposal
	Fair support for local farmers			Little is known about FEW impacts of managing food waste after it has been disposed	More money to the township government	Optimising agriculture and livestock
	Food-specific policy and regulation			Programs targeted to individual behaviours embedded within		Proper treatment facilities for pharmaceutical waste
	Formalisation by EU directives			Promote publicity and education		Provide more waste disposal infrastructure
	Government collaboration with experts			Promotion of safe animal contact focusing on the management of human waste.		Roll out food waste bins within a community
	Government fines			Promote the active cooperation of investors		Successful implementation of source segregation of food waste
	Impacts from extreme weather integrated into infrastructure decision making			Public education for handling pharmaceutical waste		Strengthen the infrastructure construction
	Interrelated policy measures			Strong environmental messaging		Supply chain innovation and infrastructure

Table A2. *Cont.*

Ecology and Health	Policy	ICT	Transport	Education	Socio-Economic	Infrastructure
	Interventions for assuring the correct development					Treatment and disposal systems
	Standardisation					Improving energy efficiency in buildings
	Local policy decisions and initiatives					Improving the efficiency of small electrical equipment
	Managing food waste to minimize its introduction into the waste stream					Real energy transition to renewables
	Multi-level governance					Reduce energy waste in projects
	Need for a roll-out of a public charging infrastructure					Market infrastructure
	Packaging eco-labelling certification					
	Policy-making and standardisation					
	Private initiatives to reduce the amount of food waste					
	Reduce the probability of government supervision					
	Tailored approaches to food waste management in rural regions					
	Water, sanitation, and hygiene strategies to reduce diarrheal disease					
	Sustainability targeted polices for Data Centres					

Table A3. Full list of Identified Barriers.

Ecology and Health	Policy	ICT	Transport	Education	Socio-Economic	Infrastructure
Pervasiveness of takeaway culture	Focus on individual country	Suspension on deployment of new data centres	Inadequate vehicle routing	Classification knowledges for WCI	Low participation rate in waste separation (17%)	Sustainable supply
Food characteristics	Inefficiencies in planting, harvesting and water use	Adoption of IoT is still in its nascent stage	Uncertainty in other transportation problems	Pharmaceutical products consumed and disposed	Growing urban populations	Many low and middle-income countries
Infectious agent may be of zoonotic rather than human	Garbage classification	Exploiting big data sources	Geographical access	Consumers’ awareness	Densely populated regions	Urbanisation

Table A3. *Cont.*

Ecology and Health	Policy	ICT	Transport	Education	Socio-Economic	Infrastructure
High export percentage of circuit boards and plastics recycling	Policy instruments (infrastructure/information) on perceived value (perceived benefit/cost)	Streamlined communications	Insufficient funds		Attitude to waste disposal	Infrastructure to harness data
COVID-19	Relies on voluntary waste diversion strategies	Lack of government regulations for IoT			Public vs. private sector participation	Imperfect and lack of infrastructure
Preventable/unpreventable food waste has different mechanisms	Actualizing energy and climate change policies	Lack of standardisation for IoT			Behavioural decision-making of individuals	Enough storage space
Proper sorting and separation of waste	The diverse priorities of stakeholders (e.g., recycling, efficiency, and effectiveness)	High energy consumption for IoT			Waste separation behaviours	Inadequate clean water resources
Reduced animal contributions	Decision-making about transitioning critical infrastructure across scale	IoT security and privacy			Public adverse reaction to new plants	Access to garbage collection
Uncertainty about weather	Decision-makers are confronted with too many challenges (societal disparities or economic instability)	IoT high operating and adoption costs			Supply chain innovation	Electric consumption forecasting in residential buildings
Low acceptance rate	Policy or societal change data	IoT long payback period			Lack of ability to shop in person	High load on the power grid
More consumption outdoors	Structural intervention	IoT lack of internet infrastructure			Cost of growing crops in a greenhouse is very high	Scarce space
Food waste management in rural regions is less studied	Impact measurement within the sector incredibly complex	IoT lack of human skill availability seamless integration			Consumer demand	Behaviour variability
Existing practices that affected social sustainability	Solid waste management (SWM) systems remain weak and lack standardization	IoT compatibility issues			Cost is significantly negatively related to WSB	
Waste results in less fish-catch	Absence of guiding policies	IoT scalability			Unwilling to pay anything additional	
Climate change	Food policy and regulation	IoT architecture			Weak public knowledge	
Perception of a high risk for human health	An improved treatment portfolio is complex	IoT lack of validation and identification			Supply chain uncertainty	
					The practices affected economic sustainability	
					Negative effect on the local economic development	
					High unemployment	

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