Review

Modern Technologies for Waste Management: A Review

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Abstract: Facing the problem of increasing waste, scientists, foundations, and companies around the globe resulted in ideas and invented technologies to slow down the process. Sources of waste range from industrial waste (e.g., construction and demolition materials, hazardous wastes, ashes) to municipal solid waste (e.g., food wastes, paper, cardboard, plastics, textiles). Modern solutions do not focus only on technological aspects of waste management but also on sociological ones. Thanks to the Internet and social media platforms, scientists can influence ecological consciousness and awareness on a much larger scale. This research was conducted using the search keywords related to modern technologies for waste management. This paper presents a spectrum of selected modern solutions that changed in recent years and how they have impacted waste management. It also discusses challenges and future directions of waste management in the context of the circular economy. The use of modern solutions in waste management allows to achieve selected goals of sustainable development.

Keywords: waste management; recycling; circular economy; pollution; media

1. Introduction

Waste production is directly related to human activities [1]. Municipal waste is produced by every human being. Their number and variety of waste grows every year. In addition to municipal waste, the second group consists of industrial waste [2], i.e., waste related to the activities of enterprises. Due to economic development and the improvement of living conditions in society, the amount of waste is also increasing [3]. The problem, and, at the same time, the challenge, is the need to manage them in accordance with the law [4].

The life cycle of waste is long and difficult. After the waste is generated, actions are taken to collect, transport, and process the waste. Municipal waste can be recycled or recovered [5]. Another possibility for their management is thermal conversion, e.g., in incinerators [6], which is combined with energy recovery. The simplest way to manage them is to subject the waste to landfill. Each of these methods has an environmental impact. However, recycling and recovery should be the preferred directions of waste management. These processes can still produce valuable products from waste.

Problems related to waste management may include, e.g., negative impacts on the biosphere, water, soil, and air pollution [7]. In order to minimize the impact of waste on the environment, appropriate action must be taken at the global, national, regional, and local levels [8]. Actions taken at the lowest, local level are important. Although there are limits to how much individuals can do to reduce waste [9]. Each of the decisions made regarding the disposal of waste has an impact on where the waste will go and whether it will be possible to subject it to the recycling process. That is why it is so important to properly implement activities related to the waste management sector in places where they are generated [10]. Most mistakes made by individuals will be impossible or difficult to correct. Another issue will be the cost-effectiveness of these activities. For this reason, more and more attention will be paid to modern, intelligent solutions that support the waste management sector.
The environmental impacts of researched products and systems can be evaluated using life-cycle assessment (LCA). The key to reliable study is clear goals, boundary settings, and quality data. Correct prerequisites will result in greater certainty in the results [11]. LCA might reveal important factors for environmental impact, which will require a special attention by researchers and officials [12]. It has proven its usefulness in the assessment of MSW strategies by evaluating the GHG, energy, and economic performances of alternative MSW management strategies by considering the interactions between social variables from 2020 to 2030 in the STLW [13].

Modern and intelligent solutions based on IT tools are increasingly being implemented in local waste management systems. They are indicated by many scientists as important in the context of implementing the smart city idea [14,15]. The use of the discussed solutions will allow waste management to be more efficient. This will be related to the preparation of better-quality raw material for recycling.

The aim of this review paper is to discuss the possibility of using modern technologies in the waste management sector. The number of new technologies in the waste management sector is considerable. The authors presented some of them, which seem to be the key in modern waste management. In this overview, research studies and commercial technologies are covered. Some focus on individuals and help them to manage their waste effectively and easily, while others allow waste processing plants to detect, disassemble, and segregate waste. The research teams conducted a literature search, considering the topics presented in the subsections. Studies were mainly retrieved from digital libraries and also other, non-scientific sources. The choice of technologies was restricted to the authors’ common area of expertise, which is computer science, electronics, and mechanical engineering. The chosen technologies caught the team’s attention as well-developed, but still relatively new and requiring research for establishing their effectiveness and profitability in real-life scenarios. The research was conducted by the search keywords related to modern technologies for waste management as such: smart waste bins, internet of things waste bins, artificial intelligence waste management, AI algorithms waste management, automated vacuum collection system, pneumatic waste pipes, e-waste processing, e-waste milling, cryptocurrencies e-waste, software waste management, and algorithm waste management.

2. Overview of Technologies

Waste management technologies have evolved in recent years, motivated by the desire to minimize the environmental impact of waste and enhance the effectiveness of waste management procedures. There is a wide range of approaches, ranging from conventional techniques like composting or landfilling, to modern, more advanced solutions using IoT technologies.

2.1. Smart Waste Bins

Municipal waste plays a huge role in waste generation. In total, 530 kg of waste per capita were generated in the EU in 2021 [16], while, generally, 4.8 metric tons of waste were generated per EU inhabitant in 2020 [17]. That gives almost 10% of the contribution to the creation of waste. It is expected that the annual solid waste generation will reach around 3.4 billion tons by 2050, and that would lead to an approximate cost of $635.5 billion in the management of municipal waste management [18]. Designing a smart waste bin has a purpose to provide an easy solution to handle all of the waste bins in a city. It is equipped with various sensors and technologies to help manage waste more efficiently [19]. These sensors can detect a wide range of data such as the fill level of the bin, gas emissions produced by the waste, humidity, weight, and many more [20]. An effective method of controlling the waste material filling level is using an ultrasonic sensor which compares the current fill level by measuring the distance between the top and bottom of the bin [21]. Then, the microcontroller compares this value with waste bin fill capacity so that it can send a notification to the authorities. Humidity and flame sensors are used to predict an upcoming fire or harmful events [22,23]. Due to smart bin sensors being an Internet of
Things (IoT) device, they can communicate with other devices/systems, such as waste management workers’ end-devices, to provide them with information about waste bin status. We should take into consideration that hardware is not everything, and that in order for smart bins to work properly, we need to take care of software that will handle all of this information. Storing data is also important for further analysis, so all of the data collected from various sensors need to be stored in a database.

Smart waste bins can be standalone devices, or they can be retrofitted onto existing bins. They can also be powered by a vast range of technologies, including solar panels, batteries, or even kinetic energy generated by people throwing out waste. By monitoring the fill level of the bin, waste management companies can schedule pick-ups more effectively, reducing the number of trucks on the road and the associated emissions. In addition to smart waste bins, RFID tags [24] with RFID sensors that are cheap and consume little power [25], and GPS tracking [26,27], are becoming a prevalent thing in waste management. RFID tags attached to waste bins or garbage trucks can transmit data about their location and status. There are several IoT technologies used to connect smart waste bins to a network. Some of the most commonly used include:

1. MQTT (Message Queuing Telemetry Transport): A lightweight messaging protocol that is designed for low-power IoT applications. It uses the publish/subscribe model, where devices publish data to a broker, which then dispenses data to subscribers [28]. This protocol uses TCP/IP for data transmission and has very strong delivery guarantees. Each waste bin can be a client to the gateway which communicates with the cloud using an MQTT bridge [29].
2. LoRaWAN (Low Power Wide Area Network): LoRaWAN is a wireless communication protocol that is being used for low-power, long-range IoT applications. It is a great choice for smart waste bins due to its long-distance data transmission and minimal power usage [30].
3. Bluetooth: It is attached for short-range communication. It may not be suitable for large-scale applications due to its limited range [18]. It can be used by a worker for maintenance in case of system failure [25,31].
4. GSM (Global System for Mobile Communications): A cellular network technology that is commonly used for communication between smart bins. It provides high bandwidth and fast data-transfer rates [31]. It is also low-cost and easy to implement.

Overall, the choice of communication technology for smart waste bins depends on various factors such as coverage, energy consumption, the cost of the technology, and the requirements of the application (Figure 1). GSM is a commonly used technology for smart waste bins, but other options such as MQTT or LoRaWAN may also be suitable.

Figure 1. Simplified Smart Waste Bin diagram.

2.2. Artificial Intelligence and Robots

Artificial intelligence (AI) has been around for a couple of decades; it can perform tasks that typically require human intelligence, such as visual perception, speech recognition, decision making, computer vision, and language translation [32]. The goal of AI is to create machines and systems that can think like us, humans, making them capable of solving complex problems and learning from experience.
Computer vision allows the interaction of robots with waste, physically. Robots can efficiently detect kinds of waste based on their visual characteristics such as shape and color [33]. It may serve a purpose in sorting waste on a conveyor belt, where individual pieces are automatically transported to the right container for further recycling. It also has the potential in spotting illegal waste dumping [34], a problem that can have a serious impact on our health and environment. By analyzing satellite images, AI-powered software could be used to locate where illegal dumping is likely to occur [35]. This can prevent further pollution and damage to the environment [36].

Effective waste recycling relies heavily on effective sorting which can be long, tedious, and requires an accurate process. In response to this, many automated systems have been developed which can do that faster and more effectively. AI systems with computer vision can distinguish types of waste [37,38] and use air pressure, magnets, or some robotic arm to separate it from other types of waste. The Finnish company ZenRobotics pioneered the technology for automated waste sorting using AI and robotics, with examples such as the Heavy Picker and Fast Picker. Where the Light Picker just has a visible light sensor, the Heavy Picker has NIR sensors, a 3D laser sensing system, a high-resolution RGB camera, an image metal detector, and other sensors. The Heavy Picker is the strongest waste-sorting robot on the market and is designed to handle big and heavy waste such as building materials or metals [39]. Robots with computer vision are able to sort recyclable materials from non-recyclable waste. AI algorithms can distinguish different types of plastic so that it can be separated. It is challenging for human workers to do it manually [40]. Moreover, AI algorithms can be used to optimize waste collection and routing which can reduce the amount of time and resources required for waste collection.

These technologies in waste management have the potential to make a significant impact. Many of the barriers could be excluded with the help of robotics, AI, and computer vision. It has the potential to revolutionize the design and operation of municipal waste-sorting plans [41].

2.3. Automated Vacuum Collection System

Most of the municipal waste is collected door-to-door by garbage collectors driving garbage trucks. It takes effort to optimize their routes with consideration of all factors. Truck travel distances are found to be sensitive to factors such as collection frequency, truck capacity, volume ratio of the truck compartment, and waste density [42]. As an alternative, a system of waste pipes called automated vacuum collection (AVAC) has been proposed and implemented over the years. The principle behind that solution is fairly simple: once waste is thrown into the inlet, it is transported by the vacuum principle through pipes into the terminal where waste is collected. Although AVAC is not the newest topic in waste management, it is still not very common. Some cities, such as Bergen, Norway, a medieval city, have adapted such a system. In 2008, Bergen’s city council decided to shift from containers to an underground waste collection system. It was opened in 2015, since then providing 24 h a day, 365 days a year access to waste inlets collecting household waste. Later in 2021, it was extended [43]. One of the most popular AVAC systems is MetroTaifun: it is present in over 40 countries, starting with the city of Makkah, Saudi Arabia, to Sejong Happy City 5-1, South Korea. This system is especially more common in Nordic countries (Finland, Norway, Sweden, Denmark) [44].

There have been theoretical studies considering economic and ecological profitability. Miller et al. [45] considered pneumatic waste pipes in a highly and densely populated area, like New York City. Current conventional waste collection requires high economic and environmental costs to sustain such an operation. In this study, three specific cases were considered: the High Line pneumatic facility, the Second Avenue Subway pneumatic facility, and alternatives for upgrading the existing Roosevelt Island pneumatic system. It was found that the costs and impacts of AVAC installations in relation to conventional collection differs due to design characteristics (i.e., the number of waste fractions, length of tube network, number of inlets) [45]. Farre et al. [46] studied a small-scale solution
in an airport over time using the Life Cycle Assessment (LCA) with ReCiPe indicators and IPCC2013 GHWP100a. These indicators provide information on impact points by categories of damage and equivalent kilograms of CO₂ emitted into the atmosphere. In a renewable energy-mix scenario, pneumatic systems have lower impact compared to truck systems, but in the Spanish national energy mix (2014) scenario it is the other way around [46]. Another LCA study was carried out by Laso et al., with specific focus on the biodegradable fraction. The results indicate higher electricity consumption by pneumatic waste pipes in comparison to door-to-door systems, when the bulky fraction includes the biodegradable fraction, but comparable consumption when the organic fraction is collected separately [47].

Teerioja et al. [48] studied a hypothetical case of the AVAC system in Helsinki, Finland. In this case, waste pipes showed a weak economic performance compared to vehicle-operated door-to-door waste collection systems. The authors suggest that unstudied technical characteristics of the pneumatic system, such as pipe diameter or different pipe routing, may significantly impact the expenses. This study also shows a significant impact of population density in relation to life-cycle costs (SLCC) [48]. Farre et al. found the majority of pipeline failures are due to attrition, mainly in elbow, connections, and piping-fitting. High glass contents and high transportation rates are the main causes of attrition. This and two previous studies show the importance of the type of transported material in regards to economic performance [46]. Application of Approximate Dynamic Programming (ADP) techniques can enhance the operation of Autonomous Vacuum Waste Collection (AVWC) systems by deriving more efficient operation policies, resulting in cost and energy savings. AVWC systems consume a significant amount of energy in their daily operation (Figure 2). Even small improvements can lead to substantial energy savings and environmental benefits. For example, a reduction of 10% to 30% in energy consumption translates to a 7% to 15% reduction in operation costs. To overcome data limitations in real topologies, Cesar Fernandez et al. employed an ADP single-pass iteration value implementation with synthetic disposal generators to devise effective aggregation methods. Building on this knowledge, we developed an ADP hybrid value/iteration policy algorithm and compared it against state-of-the-art policies based on Programmable Logic Controllers (PLCs) in real scenarios. The results demonstrate significant improvements, especially under high-load conditions [49].

![Simplified AVAC system diagram.](image)

**Figure 2.** Simplified AVAC system diagram.

### 2.4. E-Waste

Electronic waste, or e-waste, is difficult to process and is one of the fastest-growing wastes with an estimated 120 million metric tons in 2050 [50]. It contains a multiplicity of materials such as aluminum, copper, plastics, printed circuit boards, iron, steel, and hazardous components and compounds [51]. This requires disassembling and possibly further processing (Figure 3). Some parts are easily removable and might be reused right away (i.e., rechargeable batteries, motors, electronic components); others have to be processed. Recent studies show combining milling and chemical treatment methods to
be effective for retrieving metals (Fe, Cu, Sn, Al, Ni, and Zn) from PCBs [52]. Other than physical separation, like milling, electrostatic and magnetic separation can be used [53]. High stresses and the destruction of bonding in the structure of PCBs during milling makes the extracting process more efficient. A low temperature can improve the process of ball milling even further. A study shows that ball milling at temperatures as low as 154 K reduces different materials to nanoscale powders. Low temperature eliminates unwanted hazardous reactions and emissions. Overall, this method requires more energy compared to chemical and biometallurgical methods, but it allows best recovery and limited waste [54]. Although biometallurgy is not the most energy-efficient, it is the most environmentally friendly route for the extraction and recovery of metals from PCB [53].

**Figure 2.** Simplified AVAC system diagram.

**Figure 3.** E-waste recovery process flow.

Advances in technology allowed for creating reasonable standards among the devices and reduction of e-waste. Although USB-C itself has been around for almost a decade, not all manufacturers choose to use it. The USB Promoter Group continuously improves USB-C by releasing new standards adapting to power consumption and data-transfer speeds expected by consumers. The latest technical specification, USB4® Version 2.0, has been announced in September 2022. What is more, these standards are backwards compatible, meaning that you can connect two devices using different versions of USB standards and expect it to work (e.g., plug in USB 2.0 pendrive into USB 3.1 port in a computer). The European Union has taken steps to reduce e-waste legislatively. Estimates show chargers pile up to 11,000 tons of e-waste every year. In September 2021, The Commission tabled a document containing 4 proposals:

- A harmonized charging port for electronic devices: USB-C will be the common port. This will allow consumers to charge their devices with the same USB-C charger, regardless of the device brand.
- Harmonized fast-charging technology will help prevent that different producers unjustifiably limit the charging speed and will help to ensure that the charging speed is the same when using any compatible charger for a device.
- Unbundling the sale of a charger from the sale of the electronic device: consumers will be able to purchase a new electronic device without a new charger. This will limit the number of unwanted chargers purchased or left unused.
- Improved information for consumers: producers will need to provide relevant information about charging performance, including information on the power required by the device and if it supports fast charging. This will make it easier for consumers to see if their existing chargers meet the requirements of their new device or help them to select a compatible charger [55].

Although modern technologies are useful, some of them are also a source of e-waste. Cryptocurrencies are one of them. For example, Bitcoin requires a computer that performs cryptographic operations billions of times to retrieve a ‘block’ [56]. The average time of a mining device oscillates between 1.12 and 2.15 years [57]. It is estimated that, at its peak, Bitcoin consumed 204.5 TWh annually between June 2022 and July 2022, which dropped to
above 95 TWh as of May 2023. Bitcoin also generates 54.18 kt of electrical waste annually as of 13 May 2023 [58].

2.5. Software in Waste Management

Thanks to digitalization, we have the possibility to automate processes using software, including waste management. There is a broad spectrum of software concerning different target end-users. A great example of software in waste management is Artificial intelligence (AI) and the Internet of Things (IoT) [59]. It is not directly accessed by the end-user, or rather it automates manual labor conducted by them using sensors and electromechanical parts interacting with the physical world (see Sections 3.1 and 3.2 for more details). In this section, software supporting only specific fields, such as mechanical design or logistics, will not be taken into consideration.

Epifancev et al. have compared waste disposal software popular in Russia and Europe. The researchers have found that the focus of the studied software is mainly on logistics, calculation of the cost of disposal, choice of landfill, and simple interface [60]. Burger et al. [61] have gathered a sample size of n = 52 for all software, deconstructed it into sub-categories, and compared their features. An overview has shown that 40 samples can be categorized as “waste-management” in general, 30 as “recycling”, 7 as “manufacturing” and 10 as “disassembly”. This study has found software lacking features across various waste-related sub-domains. In addition, a part of the software studied has not been updated for at least 12 months preceding this study [61].

The Internet nowadays is also used as a tool for influencing ecological consciousness and helps with waste via mobile, internet, and desktop applications (Table 1). The Global Connectivity Report 2022 shows that 95% of the population is covered by broadband network (3G or recent) and 63% is using the Internet as of 2021 [62]. Applications made for a casual consumer range from ordering small packages of food that might be thrown out by your local companies, such as bakeries, cafes, and grocery shops, to pointing out illegal wastes in your neighborhood, affecting dozens of people and the ecosystem.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Type (Mobile, Website)</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reducing food loss and waste.</td>
<td>Mobile</td>
<td>Too Good To Go</td>
</tr>
<tr>
<td>Finding recycling locations (US only).</td>
<td>Website</td>
<td>Recyclenation</td>
</tr>
<tr>
<td>Creating database of illegal waste dumps and removals of them based on community reports.</td>
<td>Mobile</td>
<td>TrashOut</td>
</tr>
<tr>
<td>Generating recipes from selected products.</td>
<td>Website</td>
<td>Supercook</td>
</tr>
<tr>
<td>Recycling education platform</td>
<td>Mobile</td>
<td>Recycle Coach</td>
</tr>
<tr>
<td>Recipes for ecological cleaning products and tips on recycling.</td>
<td>Mobile</td>
<td>Ecolife</td>
</tr>
<tr>
<td>An application enabling users to easily find water refill stations for their reusable bottles.</td>
<td>Mobile</td>
<td>Refill</td>
</tr>
</tbody>
</table>

Albeit the multiplicity of waste recycling applications available, Bonino et al. [63] argue that the applications that they studied do not ensure a real engagement of end-users due to many factors, i.e., a lack of user-centered design. The authors provided a set of requirements on which they based the prototype later:

- Availability of an updated waste-collection calendar, indicating which type of waste is collected during each day of the week.
- Possibility to receive reminders with relevant collection information the day before or even during the same day.
- Access to a recycling guide, to support them during the recycling process, providing relevant information in a clear and accessible way.
- Possibility to locate waste bins near a specific place or location, together with the possibility to receive the corresponding walking directions.
• Possibility to locate nearby drop-off locations and have access to relevant information such as opening hours, provided services, and associated costs [63].

Shan et al. [64] showed that a Risks, Attitudes, Norms, Abilities, and Self-regulation (RANAS) approach for mobile app-aided behavior change might be an effective solution to encourage household recycling. The study shows a 45% household recycling rate using that approach compared to 19–22% in Singapore, as of 2020. However, the authors suggest that a larger scale test would provide better insight on scalability and sustainability due to required labor and costs in this study [64].

Algorithms are also crucial parts of software used in waste management. The SSA (Salp Swarm Algorithm) can be used to determine the amount of solid waste disposed of and recycled [65]. Dijkstra and TSP algorithms are useful to optimize the distance and transportation cost for solid waste management through the Geographic information system (GIS) software [66]. ORWARE (ORGanic WAste REsearch) is a simulation model used by researchers in waste management analysis. It calculates substance flows, environmental impacts, and costs for both organic and inorganic waste fractions. The model consists of submodels that simulate different processes in waste management. It incorporates compensatory processes for conventional production and generates data on emissions and environmental impacts [67].

Waste-related domains face barriers in adopting software; this leads to smaller businesses relying on paper-based solutions due to resistance to change and difficulty in finding suitable software packages. To address these challenges and improve software offerings in waste-related domains, software solutions should focus on better connecting additional systems with ERP solutions and databases. In addition, implementing real-time information capabilities can greatly benefit the software’s functionality. Implementing these recommendations can encourage the adoption of advanced software solutions in waste management [61].

3. Discussion

This study aimed to show a potential that modern technologies have in waste management. The presented studies prove that there is a big potential in improving and automating processes in each step in the waste management hierarchy.

The smart waste bin is an innovative technology that uses sensors and Internet of Things connectivity to optimize waste management processes. Sensors attached to a bin can detect the level of waste inside and other parameters such as temperature and humidity. With this data, waste management companies can be equipped with real-time information about the waste status and use this information to provide more efficient services. However, there are also disadvantages. The cost of the smart waste bin is significantly higher than the regular waste bin. We have to keep that in mind that waste bins should be almost everywhere in the city. Smart waste bins are also bigger and repairing costs can be painful for the authorities. These devices need to be maintained regularly, which is also a cost. It is crucial to acknowledge “technological literacy” of society in such systems. If a solution requires interaction with a user (i.e., opening the bin via touch screen), it should be reduced to a minimum.

Internet coverage plays a big role in the implementation of waste bins. Solutions in urban and sub-urban areas with less developed internet infrastructure might require other wireless solutions for better stability and connectivity; further research should consider alternatives, such as LoRaWAN, for greater usability in various areas. It is worth noting that license-free frequencies vary between continents. For LoRa these are some of the bands that are license-free (ISM): EU868 (863–870/873 MHz) in Europe; AU915/AS923-1 (915–928 MHz) in South America; US915 (902–928 MHz) in North America; IN865 (865–867 MHz) in India; and AS923 (915–928 MHz) in Asia [68]. These legal issues should be emphasized by researchers for clarity and easier replicability by others.

Governments can encourage the adoption of smart waste bins by providing tax breaks to waste management companies, so they would feel more confident to invest in that
technology. Future research can investigate how smart waste bins can be improved. At the
time of writing this paper, many available smart-waste-bins-related resources are pretty
similar to each other or do not provide any significant innovations (i.e., different types of
sensors, alternative energy sources), so the research may not be entirely covered and need
to be carried out once more in the future.

Artificial intelligence and robots are being increasingly used in waste management.
AI algorithms not only speed up processes but they also improve their accuracy and safety.
AI can be used in various situations, from powering machines to predicting where illegal
dumping may occur using photos from space. Computer vision has shown significant
promise in tackling the global waste management crisis, using its ability to distinguish types
of waste based on visual characteristics. AI capabilities are able to enhance waste recycling
rates and optimize waste collection. Robots can do their job faster, more efficiently, and more
precisely than humans constantly learning about a given task. Using these technologies
can significantly increase waste management effectiveness. However, it will be a challenge
to implement AI in waste management successfully. The cost and scalability of AI systems
are uncertain. Furthermore, as with any automation, the risk of job displacement for waste
management workers needs to be acknowledged and managed. AI-related topics are a
contemporary concern these days because of the OpenAI GPT-4 language model. It proved
to us that nothing related to AI is certain yet, so further research may be needed to cover
the impact of GPT-4 and other AI language models in practical reality.

The implementation of automated vacuum collection (AVAC) is an alternative to
traditional door-to-door waste collection implemented in various cities worldwide. Studies
have been conducted to evaluate the economic and ecological profitability of AVAC systems
compared to the traditional waste-collection method. While the principle behind the system
is simple, it requires careful consideration of factors such as pipe diameter or pipe routing.
We cannot forget that, based on the study carried out by Laso et al. [47], pneumatic waste
pipes, in comparison to door-to-door systems, consume more electricity when the bulky
fraction includes the biodegradable fraction. Also, Farre et al. [46] found that the majority of
pipeline failures are due to attrition; studies show the importance of the type of transported
material. Further research is needed to fully evaluate the effectiveness and long-term
impact of AVAC systems depending on specific cases. It is also important to consider
different energy sources in those cases as they may change the results. Other than overall
efficiency, the wear out of the system as a whole should also be deeply studied, as this
system was proven to be prone to attrition. The proposed and implemented AVAC systems
might be improved by using AI for waste segregation, so that unwanted content does not
end up in the same collector as the rest. As for pipes, the inside walls might be coated with
already-existing solutions or a new, researched one.

E-waste is a type of waste requiring complex processing: disassembly, mechanical
treatment, and chemical treatment. Studies show that cryo-milling, a technique that
involves freezing e-waste before grinding it down into small particles, might be the future
of e-waste processing. Cryo-milling produces the lowest waste and recovers the most
materials in comparison to the physical method, the chemical method, and biometallurgy.
It also has a lower environmental impact by reducing unwanted reactions and emissions.

Standardization amongst electronic devices may lead to reducing e-waste in general.
Further research should consider the effects of legislative steps taken by organizations to
unify used technology. It also might suggest adjustments for lowering the economic and
ecological impacts and indicate technologies where unification is possible. Another topic
worth considering towards the reduction of e-waste through legislation is complementary
goods. Devices often come with additional items such as cables or headphones. It is
important to research the amount of e-waste generated by these items, which might turn
out to be a significant percentage of overall e-waste.

Many cryptocurrencies generate huge amounts of e-waste due to their demand for
power while mining. Bitcoin itself consumes almost as much power as the country. Devel-
opers can see this, and they are trying to achieve less demand for power. A good example
could be “The Merge” in the Ethereum algorithm, which changes the energy consumption of this coin by ~99.95% [69]. Currently available research papers lack a condition assessment of post-mining hardware. Graphical processing units (GPUs) are constantly exploited while mining cryptocurrencies. While miners on forums suggest that the under-volting of the lifespan of hardware is increasing, it has not been unequivocally stated through research. Central processing unit (CPU) faultiness on the other hand has been studied for consumer-class computers. It has been found that they are less likely to be faulty by 39 to 80% due to under-volting [70]. Some similarities in construction of both units might suggest that they react similarly; nevertheless, mining hardware should be studied separately due to constant load in opposition to personal computers.

Using software in waste management is an incredibly convenient thing. Internet connectivity and the multitude of mobile and desktop applications have made it easier for end-users to participate in waste management activities, promoting ecological consciousness. Software automates processes, analyzes data, and can be easily extended with more functionalities.

But, end-users must consider that a community is developing some of these apps. Unfortunately, it may be hard to find applications with verified content so be aware of that. Bonino et al. [63] emphasized the need for a more user-centered UI (User Interface) design, and extended functionalities in waste management applications to enhance user engagement. Anyway, using some of these can have a positive impact on our lifestyle. Due to the large number of applications released every year, further research may be needed to distinguish their usefulness and impact on the environment and society. Many application developers try to promote their products as ecological and pro-social, but only in-depth research can determine which of them live up to their promises and are worth attention (Table 2).

<table>
<thead>
<tr>
<th>Disadvantages</th>
<th>Advantages</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher maintenance cost, need for device maintenance</td>
<td>Optimization of waste management processes, real-time data delivery</td>
<td>Smart waste bin</td>
</tr>
<tr>
<td>Uncertainty about the long-term impact on work</td>
<td>Improved efficiency, and security, predicting illegal waste dumping, distinguishing types of waste</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>Higher energy consumption, Failure rate of the pipeline system</td>
<td>Improved waste collection efficiency, worldwide implementation possible</td>
<td>Automated vacuum collection system</td>
</tr>
<tr>
<td>Difficulties in verifying the content of the application</td>
<td>Processes automation, real-time data analysis, ease of interaction</td>
<td>Software</td>
</tr>
<tr>
<td>The complexity of the e-waste processing</td>
<td>Efficient material recovery, low environmental impact</td>
<td>Cryo-milling</td>
</tr>
<tr>
<td>Need for a change at the legislative level.</td>
<td>Reducing the amount of e-waste</td>
<td>Electronic standardization</td>
</tr>
</tbody>
</table>

4. Conclusions

In many cases, economic growth and development have a negative impact on the environment. Issues related to sustainable development, environmental protection, and the circular economy are gaining in importance every year. A special role in these activities is played by waste. The production of waste cannot be avoided, but it can be limited or managed wisely. According to the assumptions of the circular economy, the generation of waste should be minimized and as much of it as possible should be used in the recycling process. This will certainly be one of the biggest tasks in the coming years. Waste management is one of the areas that deserves special attention. In the case of rational actions, seemingly unnecessary waste often turns out to be a valuable raw material. Incinerating or landfilling
of waste results in the loss of valuable resources. For this reason, measures should be taken to collect them properly and prepare them for reuse.

The use of modern technologies in waste management has the potential to reduce the overall environmental impact. Improvements may be made, not only by increasing the productivity of the whole processing system, but also by impacting sociological aspects, such as ecological awareness, to lower non-recyclable waste and reduce waste overall. This study has focused on both theoretical cases and practical implementations of these technologies. Advanced software, alternative waste transportation, modern communication standards, and sensor-based waste management are only a fragment of modern technologies that may help to reduce waste and provide economic and environmental benefits. However, it should be emphasized that many solutions in the field of modern technologies for waste management are expensive, which significantly limits the possibility of their application. In addition, their use is associated with special technical requirements, which are not always possible to apply. However, technologies have advantages and disadvantages that must be evaluated before implementation. Further research is needed to fill the knowledge gap about the effectiveness of the presented technologies, depending on the application they are used for.

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