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Article

A Management Framework for Municipal Solid Waste Systems and Its Application to Food Waste Prevention

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Abstract: Waste management is a complex task involving numerous waste fractions, a range of technological treatment options, and many outputs that are circulated back into society. A systematic, interdisciplinary systems management framework was developed to facilitate the planning, implementation, and maintenance of sustainable waste systems. It aims not to replace existing decision-making approaches, but rather to enable their integration to allow for inclusion of overall sustainability concerns and address the complexity of solid waste management. The framework defines key considerations for system design, steps for performance monitoring, and approaches for facilitating continual system improvements. It was developed by critically examining the literature to determine what aspects of a management framework would be most effective at improving systems management for complex waste systems. The framework was applied to food waste management as a theoretical case study to exemplify how it can serve as a systems management tool for complex waste systems, as well as address obstacles typically faced in the field. Its benefits include the integration of existing waste system assessment models; the inclusion of environmental, economic, and social priorities; efficient performance monitoring; and a structure to continually define, review, and improve systems. This framework may have broader implications for addressing sustainability in other disciplines.

Keywords: municipal waste management; management system; waste system; municipal solid waste; planning; food waste; waste prevention; interdisciplinary; sustainability

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1. Introduction

Effective management of municipal waste systems requires a good understanding of waste disposal drivers, quantities of waste generated, economic costs of system operations, and the environmental impacts of treatment technologies. Furthermore, waste systems must be managed in a comprehensive, interdisciplinary manner which allows for the incorporation of local concerns and social priorities as well as evolution with changing situations and needs. This approach, which stems from Systems Theory, emphasizes that holistic approaches are needed to implement effective changes within a system [1]. A systems analysis of waste management aims to provide a picture as complete as possible of the whole waste system [2] in order to assess the consequences of various decisions affecting it. To address sustainability, a systems analysis should focus on environmental, economic, and social system components. With this in mind, a management framework for planning, implementing, and maintaining waste systems was developed which emphasizes sustainable decision-making and the integration of various system analysis tools. The interdisciplinary framework is important for complex solid waste management as existing waste management modeling and decision-making approaches tend to focus solely on technological, financial, or environmental assessments and do not address the interdisciplinary nature of waste policy or the importance of social criteria [3,4].

The development of the framework is first described, followed by a theoretical application of it to address sustainable food waste management, particularly prevention policies. The framework can assist with combating key obstacles encountered when establishing a food waste management program, and does so in a way which encourages success at various levels within a system. A theme of the framework is that effective waste management systems must successfully integrate knowledge from many disciplines, including engineering, science, policy, economics, sociology, and ethics, and be grounded in local conditions. It measures success across a range of indicators and enables these indicators to be tracked over time, which ultimately helps yield continual system improvements.

Because waste management has become increasingly complex, there is an increased need for synergistic management approaches which integrate existing assessment models as well as greater public engagement within the political and institutional decision-making sectors [5]. Various systems engineering models and assessment models for waste management have been used over the past several decades, such as life cycle assessment (LCA), materials flow analysis, optimization analysis, simulation analysis, environmental impact assessment, and cost-benefit analysis, among others [6]. However, there is an immediate need to integrate these existing systems assessment approaches into a single system-wide approach to yield a comprehensive approach to waste management [6,7]. An integrated, interdisciplinary management structure, such as the framework developed here, which includes all three aspects of sustainability (environment, economic, social), can facilitate waste system improvements.

Some recent work has begun to emphasize the importance of multi-disciplinary system-wide approaches to waste management that include social aspects. Social aspects include employment, acceptance, equity, motivation, interest, and participation [8]. Finnveden *et al.* [9] suggested that social criteria, including social fairness and cultural effects of policies, in addition to economic and environmental factors, are important for sustainable waste management policies. Klang *et al.* [2] identified that a range of aspects, including working conditions for waste sector employees and low system cost, are important to include in a waste systems analysis. Salvia *et al.* [10] examined improvements to resource efficiency for energy and waste through multi-faceted municipal urban planning, with key components including effective stakeholder engagement and behavior-changing measures. Li *et al.* [11] assessed Chinese waste management by integrating an assessment of environmental effectiveness, economic efficiency, and social health safety, with emphasis on including stakeholder opinions.

However, methods for incorporating social aspects into waste system design are still considerably less mature than methods for environmental and economic waste system assessments [12] and most studies exclude social aspects [13]. Although the integration of public values with technical analysis is important for effective waste management [5], current literature indicates that most existing waste models and decision-making approaches tend to exclude the public from decision-making processes and fail to consider all relevant stakeholders [4]. Governments generally oversee waste management, but their actions alone are far from sufficient to achieve sustainable waste management; rather, local-level involvement is important, especially through engagement of the general public [14]. Another limitation of existing waste management analysis approaches is that they tend to lack clear definitions of system priorities [15]. Furthermore, there is currently no consensus on the best way to integrate methods for sustainability assessment since such an assessment is dependent on the purpose of analysis and specific local factors [16]. These shortcomings of existing approaches have led to calls for an improved methodology for sustainable waste management which integrates findings from multiple assessment methods [7], includes concerns of all community stakeholders, and enables detailed assessment at all stages of a system's progression (development, implementation, evaluation) [4]. The objective of this study was to develop a framework which fills these gaps and facilitates waste system management. This framework is proposed as a means to address the need to integrate existing waste models (e.g., LCA, cost-benefit analysis) in a way which accounts for overall sustainability concerns and emphasizes social priorities, thus enabling better decision-making for sustainability. This framework was designed to be broad enough to allow for easy integration of local knowledge and approaches, as well as project specific concerns, thereby facilitating its incorporation into extant waste management structures.

2. Framework Development

Waste management is a complex task involving numerous waste fractions, a range of technological treatment options, and many outputs that are circulated back into society [17]. There are many diverse stakeholders involved and various markets for system outputs (e.g., energy, nutrients) [17]. Waste systems involve multi-faceted tradeoffs to be considered among technologies, some of which are advanced and novel, economic instruments, and regulatory frameworks [7]. The complexity of these systems indicates that a systems perspective is critical for understanding system dynamics. Furthermore, because waste systems frequently change over time [18], management approaches should allow for evolution and improvement. Sustainable waste management systems, in particular, are environmentally effective, economically affordable, and socially acceptable [19]. So, systems must relate to local environmental, economic, and social priorities and encourage stakeholder and public engagement in decision-making [5,15,20]. Such complex management situations for already complicated systems are better handled if they are supported by tools for evaluating overall system dynamics which integrate these concerns [21].

Here, a systematic, interdisciplinary systems management tool was developed to facilitate the planning, implementation, and maintenance of sustainable waste systems. The framework was developed by critically examining the literature to determine what aspects of a management framework would be most effective at improving systems management for complex waste systems. A systems approach was used to ensure that the framework addressed all aspects of a waste management system, including both technical aspects, such as treatment technologies, and nontechnical aspects, such as regulations, policy measures, and social implications. Existing generic systems management tools, particularly the ISO 14001 environmental management standard, were reviewed to determine what aspects of it would and would not be useful for waste systems. Next, existing waste management system assessment models/methods were examined to determine their usefulness and their deficiencies. Addressing their deficiencies was a key priority for framework development. Last, known challenges with current waste management practices were explored to assess which factors would be important to incorporate into the framework to address these issues.

2.1. Key Factors of Existing Generic Systems Management Structures and Their Applicability to Waste Management

Existing management system structures, particularly the ISO 14001 standard for the development, implementation, and maintenance of environmental management systems (EMS) developed by the International Organization for Standardization (ISO), were reviewed to identify important factors for systems management that would be crucial to incorporate into a management structure for waste systems. The ISO 14001 standard has been adopted by a range of organizations since its creation in 1996, primarily in Europe and Asia [22]; almost 286,000 organizations worldwide have an ISO 14001 certified EMS [23]. It includes 18 elements: establishment of EMS scope; environmental policy; environmental aspects and impacts; legal and other requirements; environmental objectives, targets, and programs; resources and responsibility; competence and training; communication; documentation; control of documents; operational control; emergency preparedness/response; monitoring and measurement; evaluation of compliance; corrective and preventative actions; control of records; internal auditing; and management review (ISO 2004).

There were several important aspects of the ISO 14001 standard that appeared to be useful for waste management systems; these factors were incorporated into the waste framework. Like ISO 14001, the waste framework defines an approach to manage systems, including defining objectives, setting targets, defining regulatory and other requirements as well as personnel responsibilities, and monitoring improvements. A desired outcome of the framework is to allow for continual improvement in system performance over time, shared with the ISO 14001 standard. Both approaches are general; they are meant to be adapted by a variety of organizations, ranging in size, function, and purpose.

Besides similarities in the overall structure of the framework and ISO 14001 standard, specific details differ considerably as not all aspects of the ISO 14001 standard are useful for waste management systems. The framework is designed specifically for waste management systems through integration of waste-specific concerns. Also, instead of focusing solely on environmental performance, the framework encourages an interdisciplinary sustainability-focused approach to systems management which integrates environmental, economic, and social factors. The framework is less rigid than the ISO 14001 standard to allow for easy integration of local knowledge and approaches, thus facilitating its incorporation into pre-existing waste management systems. Unlike the ISO 14001 standard, the waste framework does not involve tedious and time-consuming practices [24]. Instead, it aims to be relatively easy and quick to implement, making it time- and cost-effective.

An issue with waste management systems is that managers often lack the resources and time to implement complex management approaches. A summary of the experiences of four waste organizations that implemented an ISO 14001 EMS found that large expenditures of time and money were required to implement and maintain the systems [24]. Kent County, MI, reported that their expenses were approximately $25,000 to implement an ISO-14001 EMS for their landfill, and significant time from county employees was required, including at least 10 to 20 h from a dedicated environmental compliance manager. In King County, WA, the implementation costs for a waste facility EMS were between $44,000 and $72,000 annually for three years. It required about 1000 to 1200 personnel hours per year for three years, and maintenance required 200 to 250 personnel hours per year [24]. A time-intensive, expensive EMS is not ideal for many waste systems, particularly due to limited resources. Furthermore, a generic EMS does not account for concerns specific to waste management and it does not incorporate economic or social factors, all of which are priorities for the development of the framework.

2.2. Existing Waste Management Systems Models/Assessment Methods and Their Deficiencies

Chang *et al.* [6] reviewed existing waste management assessment methods and identified 14 systems engineering and assessment tools for waste management systems (e.g., LCA, materials flow analysis, optimization analysis, simulation analysis, environmental impact assessment, and cost-benefit analysis). Benefits can be achieved by using these tools and their use can ultimately improve waste management decision-making [25]. Therefore, the use of these existing tools is essential for waste systems management, thus indicating they should be a key component of the framework.

However, traditional waste planning models generally focus solely on technological, financial, or environmental systems; few refer to the interdisciplinary nature of policy, and most do not analyze social criteria [3]. Several reviews of waste management assessment models [4,6,7,26] all concluded that models tend to focus on one or two issues rather than take a holistic, interdisciplinary view of waste systems. This was substantiated by Allesch and Brunner [13] in their recent review of 151 waste system assessment studies which found that most focused on environmental impacts, about half included economic impacts, and only a small number included social aspects in analyses. Few included all three aspects of sustainability. For instance, Eriksson *et al.* (2014) included economic and environmental aspects in their systems analysis of a Swedish waste system, but omitted consumer perspective. Papargyropoulou *et al.* [27] examined envionmental and economic effects of food waste management, but did not include a cost-benefit analysis of economic impacts. Cucchiella *et al.* [28] looked to find optimal management approaches for Italian waste systems by maximizing environmental and financial aspects. They noted that sustainable management requires inclusion of social aspects, particuarly health effects, but these were not fully included in the analysis.

The framework aims to integrate existing waste management models, which has been identified as a critical need in the literature [6]. It emphasizes the use of both quantitative and qualitative tools which address environmental (e.g., LCA), economic (e.g., cost-benefit analysis), and social (e.g., stakeholder analysis) factors.

2.3. Challenges with Existing Waste Management Systems and Necessary Improvements

There are several areas of deficiency in current waste management practices that were identified and then integrated into the framework in order to improve the management of municipal waste management systems. A major aspect of the framework is the integration of diverse stakeholders into waste planning, implementation, maintenance, and evaluation, which generally has not been extensively performed previously. This involvement not only allows for reflection of concerns and interests of stakeholders, but also extends the knowledge base for decision-making [5]. National, state, and local governments, technical experts (e.g., academics, consultants), legal representatives, funding agencies, community groups, media, industry, and the general public play major roles in supporting waste policy actions and their inclusion facilitates effective planning. Identifying stakeholders and their interests is necessary to ensure their participation and involvement in waste management [15] and this was incorporated as a key aspect of a framework. The inclusion of stakeholders also helps identify specific political pressures (e.g., political acceptability) and goals (e.g., resource recovery, reduced emissions, energy recovery) which often drive waste initiatives. Table 1 outlines key stakeholders and examples of their roles in waste management.

Another key aspect of the framework is the collection and monitoring of data to assess system performance. There often are insufficient data and metrics in waste management, which restricts complete policy evaluation [29–31]. A key component of a successful management system involves stipulations for comprehensive data collection which enables waste managers to assess system performance. Complete, accurate data enable quantitative-based policy-making and target-setting. Furthermore, increases in the number of well-managed waste systems with complete data collection will improve the overall data situation for global waste systems as a whole. This enables managers to compare performances from one system to another, and to learn from successes and failures of others.

Part of the data collection process involves collecting sufficient data to examine performance indicators that address relevant environmental, social, and economic concerns. Thus, in addition to including indicators focused directly on managed wastes, it also is important to incorporate indicators that address other sustainability issues such as waste prevention, public education programs, affordability, and extent of stakeholder engagement. This was emphasized in the framework. Wilson *et al.* [32] support the use of performance indicators for waste systems that extend from physical and technological system components to sustainability aspects (social, institutional, political, financial, economic, environmental, technical) and stakeholder concerns. Greene and Tonjes [31] defined evaluation criteria for waste management system performance indicators (Table 2). These criteria should be included when deciding on indicators using the waste management framework.

Table 1. The roles of stakeholders in sustainable waste management.

Stakeholder	Examples of Roles
National and state government	Set environmental regulations; support local municipalities
Local government	Monitor system performance; drive public education; set targets/objectives; ensure availability of adequate human and financial resources; provide infrastructural inputs and services; enforce regulations
Technical experts	Determine which technologies and policies are most effective; conduct assessments, such as life cycle assessment (LCA) or cost-benefit analyses; drive innovation
Policy makers	Develop polices
Social services	Address social concerns, including job creation and environmental justice
Funding agencies	Support/fund projects
Legal representatives	Develop legal regulations; ensure adherence to legal requirements
Community groups	Promote local concerns
Media	Contribute to environmental awareness; inform the public about major issues
Waste and transportation industries	Mange wastes as dictated by policy; drive innovation
General public	Participate in decision-making regarding effective programs ; adhere to waste policies; pay for waste services; assist in identifying sites for waste facilities; work in waste management facilities

Table 2. Waste system performance indicator evaluation criteria (modified from [31]).

Criteria	Definition
Direct	Indicator measures closely to the possible result it is intended to measure
Objective and Specific	No ambiguity in measurements; indicator is clearly defined and uses common definitions
Clear	Indicator should be simple and easy to interpret
Practical	Data can be obtained timely at reasonable costs
Reliable	Data for indicator is of sufficient, dependable, and consistent quality for decision-making
Useful for Waste Managers	Indicator provides meaningful measurement of system change; indicator is useful for daily decision-making regarding system; indicator indicates progress towards improved system design
Relevant	Indicator provides information that is of priority interest; indicator is important for communicating information about systems

2.4. Framework Objectives

The overall goal of the framework is for it to serve as a practical tool for the sustainable management of waste systems. The specific objectives of the framework were developed based on the identified needs for waste management as indicated in the development phase. Some framework aspects are already conducted to some degree in waste planning as a result of regulatory requirements, such as facility permitting, but the framework helps ensure that all key aspects are acknowledged and that the system is continually monitored over time. It aims not to replace existing decision-making approaches, but rather to enable their integration to allow for the inclusion of overall sustainability concerns and address the complexity of solid waste management. Specific objectives are:

1. Allow for system components to be well-defined
2. Maintain compliance with applicable regulations
3. Integrate environmental, social, and economic concerns and assessment approaches into waste systems
4. Enable data collection and performance assessment
5. Allow adjustments to be made over time for improvement

This framework was designed for municipal solid waste management, although it may be extended to other waste systems, such as industrial wastes. It also may have broader implications for other types of environmental planning; the framework's interdisciplinary nature may be used to address the complexities of other systems, such as in the energy and ecological sectors.

3. Results

There are four overarching components of the framework: Plan, Implement, Evaluate, and Improve (Table 3). The purpose of the first overarching principle, Plan, is to encourage municipalities to clearly define overall system objectives and to define which programs are necessary to achieve them. By starting the framework by defining overall objectives, managers can integrate these objectives throughout the whole system as they work through the steps of the framework. A key aspect of the Plan component is that the regulatory and financing structures of the system, as well as the population targeted by waste system policies, must be clearly defined. The Plan component also emphasizes stakeholder outreach, which aims to improve stakeholder relations and to leverage their expertise. One of the most important components of the Plan stage is the use of existing system assessment tools (e.g., cost-benefit analysis, LCA) and the combination of their findings to yield a comprehensive view of the waste system. The Plan stage is critical for system success as it encourages planners to think through many of the key components of the waste system in light of overall objectives.

The next overarching principle, Implement, refers to the daily operations of the system. A key aspect of this component is defining targets and performing regular data collection to assess progress towards objectives and targets. An issue with many solid waste systems is the lack of accurate and complete data [29,30]. The framework aims to address this issue by encouraging regular, comprehensive data collection. Successful implementation of this framework is based not only on waste diversion rates or economic criteria, but also on stakeholder engagement, fulfillment of social priorities, and other concerns. The purpose of the Evaluate principle is to evaluate system performance and to critically analyze challenges that have been experienced. This is an important step, especially after the framework has been implemented for some time, to determine if system objectives are being achieved. The final overarching principle is Improve. This principle encourages frequent review of the system and its performance, and modification if necessary. Modification of aspects of the Plan stage should be done as necessary (e.g., update legal requirements if new regulations are passed). The framework is intended to be used continuously so that systems are repeatedly evaluated and improved.

Table 3. Management framework for waste management systems.

Overarching Component	Step	Description
Plan	1. Define system	a. Define scope of system (e.g., scale, time-frame) b. Define system boundaries c. Define overall system objectives, including environmental, social, and economic objectives. Integrate local concerns d. Clearly state definitions for key terms
	2. Programs and Policies	a. Determine programmatic (including technological and policy) options for achieving overall objectives b. Evaluate the program with regards to Steps 3–8 of the framework. Perform detailed assessments, including optimization analysis or simulation analysis, as necessary
	3. Requirements	a. Identify and/or define applicable legal requirements b. Identify and/or define other applicable requirements (e.g., institutional)
	4. Resources	a. Define required economic resources; consider long-term funding b. Define other required resources (e.g., human resources, specialized skills) c. Ensure required resources are available. Perform detailed cost assessments, such as cost-benefit analysis, as necessary
	5. Responsibilities	Define roles and responsibilities for system managers, other personnel, and stakeholders
	6. Environmental Impacts	Evaluate environmental impacts of program. Use LCA or another comprehensive approach if possible
	7. Stakeholders and Social Impact	a. Identify stakeholders and their concerns regarding the system b. Define methods for stakeholder communication, including regular outreach and education; include approaches for integrating their knowledge and concerns early in the planning process c. Identify impacts of program on society (e.g., job creation)
	8. Measure	a. Identify and define performance indicators which are measureable and consistent with the overall system scope and objectives; include environmental, financial, regulatory, social, and stakeholder concerns (as identified during previous planning steps) b. Define methods for ensuring sufficient and regular data collection
	9. Select Program/Policy	Select the best program option based on findings from Plan steps
Implement	10. Targets	a. Identify specific targets based on the indicators selected in Step 8 b. Define the means in which target will be achieved and set time-frame for achievement
	11. Implement program	Implement the program
	12. Collect data	Collect data according to plans outlined in Step 8
Evaluate	13. Evaluate progress	a. Determine if overall system objectives and specific targets are being achieved (as identified in Steps 1 and 10) b. If achievement is not reached, identify reasons why
	14. Evaluate compliance with requirements	Determine if compliance with requirements (as identified in Step 3) is achieved
	15. Challenges	Identify challenges observed within the system
Improve	16. Programmatic changes	a. Identify ways to improve existing programs, especially if targets are not achieved b. Plan and implement new programs if necessary (use Steps 1–9)
	17. Revise Targets & Continue	a. Revise targets based on current performance b. Modify other components of the Plan stage as necessary c. Continue following the framework to repeatedly evaluate the system allowing for continual improvements

The framework may be applied to a whole system (e.g., whole waste management system) or to a specific component of a systems (e.g., food waste management system). It may be used at various system stages; it can be first used as a planning tool to design or decide on a new program, policy, or technology and then to evaluate outcomes, or it can be used to evaluate an existing program, and then make improvements. It can be used to prevent waste or to manage waste effectively after it has been generated. The framework should be followed in order and documentation for all steps should be performed. However, unlike the strict, time-consuming documentation requirements of ISO 14001, the framework allows managers to perform documentation and document control in any manner they choose, which facilitates its integration with current practices. It is possible to perform the Plan steps multiple times if there are various programmatic options being considered. This facilitates the comparison between options and the selection of the optimal option. If this approach is utilized, once the best option is selected, the rest of the framework (Implement, Evaluate, Improve) should be followed. The framework is purposely general so that it may be utilized by a range of waste management systems and local considerations can be incorporated.

3.1. Guidance on Using the Framework for Planning

Table 4 provides guidance on key considerations for decision-makers when using the framework for waste system planning. It shows the questions that should be addressed when selecting among policy or technology options. It is possible to set up a decision matrix using the framework as a guide to systematically and quantitatively compare one option with another. The table is not meant to be an exhaustive list of considerations, but is provided to demonstrate how the framework can guide decision-making.

Table 4. Key considerations as guided by the framework.

Step	Questions to Consider
1. Define system	What is the scope of the project? What system objectives do you want to achieve? What is the overall timeline for the project?
2. Programs and Policies	What policy options are under consideration? Which policy option aligns best with system scope and objectives? Does the policy allow for changes to be made to it over time?
3. Requirements	Does the policy align with existing legal and other requirements? If new regulation is required, is it feasible to implement within the existing regulatory environment? Is there a way to ensure compliance with the policy? If so, how?
4. Resources	What is the financial cost to implement and maintain the policy? What human resources (e.g., staff time) are required to implement and maintain the policy? Are there any other specialized resources that are required? Are the required resources available? If not, how will you ensure that they are available? Is the infrastructure required for the policy in place? Are there means to facilitate public compliance with the policy (e.g., economic incentives, technical assistance)?

Table 4. *Cont.*

Step	Questions to Consider
5. Responsibilities	What roles and responsibilities are required for managers? Is this feasible? What roles and responsibilities are required for other personnel? Is this feasible?
6. Environmental Impacts	What are the environmental impacts of the policy? What are the main factors that affect the environmental impact of the policy (e.g., travel distance of waste to processing facility)? What local environmental issues are of concern?
7. Stakeholders and Social Impact	Who are the main stakeholders? How will you reach out to stakeholders and incorporate their concerns into the policy? What are the concerns of the main stakeholders? Who will be in favor of the policy? Why? Who will be in opposition of the policy? Why? Will the policy provide social benefit (e.g., job creation)?
8. Measure	Do performance indicators reflect system objectives? Do performance indicators address issues from various sustainability issues (economic, social, and environmental)? Are the performance indicators clear, specific, practical, reliable, useful, and relevant? Are means for data collection feasible? Is there room to improve the system over time? What are the expected obstacles to implementing and maintaining this policy in the short-term and long-term?
9. Select Program/Policy	Which program/policy: aligns best with your system? enables system objectives to be achieved? is acceptable to stakeholders? is feasible to implement within timeframe?

4. Discussion

The framework was applied to a waste system focused on food waste management to demonstrate the benefits of using the framework. Food waste was selected due to the complexities of managing this component of the waste stream and its importance for global sustainable waste management. Food waste has been identified as a significant social, economic, and environmental problem [33], and the implications of this element of the solid waste stream have become a topic of growing interest worldwide. It has been estimated that food waste makes up nearly 15% of the disposed waste stream in the U.S., and Americans have been disposing about 0.28 kilograms of food waste per person per day over the past two decades [34]. Globally, the production of lost and wasted food accounts for 24% of total freshwater resources used in food production, 23% of global cropland, and 23% of global fertilizer use [35].

Food waste prevention is seen as a way to mitigate some of the harmful impacts of food waste in waste management systems and in global food systems. Avoidance of food waste has the highest environmental benefit relative to other waste management approaches due to the reduced environmental impacts gained from avoided food production [36,37]. Food waste avoidance can also reduce social and economic harms of food waste. Reducing food waste across the entire food chain has been identified as an essential component of strategies to sustainably and equitably achieve global food security and feed the world's growing population [38,39].

There are regulatory, social, and political obstacles to enacting food waste prevention policies. The waste management framework can help ensure that these issues are addressed prior to the implementation of policies (planning stage), as well as throughout the system lifetime (system implementation and maintenance), and it assists with improving the system over time to address current and future obstacles (Table 5). It encourages engagement, communication, and interchanges of information across diverse stakeholders in food and waste systems to effectively prevent waste. Another benefit of using the framework is that it facilitates the integration of multiple existing systems analysis approaches, such as economic and environmental analyses, as well as qualitative societal analyses, which examine how society will respond (e.g., acceptance) to policy options and effects on society (e.g., job creation). The framework's general nature makes it practical and affordable to implement, unlike ISO 14001, which was shown to be difficult and costly for waste managers to use [24]. Its generality makes it relatively easy to integrate with extant waste programs. It also facilitates the inclusion of achievable outcomes, as managers define objectives and measureable targets based on the needs and conditions of the system. Here, key challenges associated with food waste prevention policies and ways in which the framework can be used to address them are discussed.

Table 5. Using the framework to address challenges with food waste prevention.

Challenges	How Framework Addresses It
Poor Public Participation	Clearly defined target population; carefully planned initiatives and integration of stakeholder concerns
Inconsistent Definitions	Stipulations for definitions of key terms
Lack of Complete Data	Stipulations for continual data collection and analysis; well-defined performance metrics
Lack of Effective Indicators to Evaluate System Performance	Guidance on indicator development which cross disciplines
Perceived High Costs	Thorough assessment of economic costs of policies can be used to encourage behavioral changes
Little Stakeholder Engagement	Engagement of a range of stakeholders for policy development
Uncertainty Regarding Policy Performance	Consistent, thorough data collection and indicator monitoring will provide future guidance on policies that are effective and those that are not; the integration of existing assessment models can clarify the effects of policy options

4.1. Poor Public Participation

Many source-separation programs for traditional recyclables have not succeeded because of insufficient or un-sustained citizen participation [40]. To address this, the waste framework encourages stakeholder engagement, especially from the public and community groups, early in the policy planning process. This communication can indicate consumer perceptions of food waste and which policies will resonate with them [39]. Assessing motivations for wasting food and openness to a prevention program may be an appropriate means to determine which efforts will be effective. A survey in Greece indicated that people had positive attitudes towards reducing food waste, they were concerned about food waste, and they understood good habits for reducing waste [41]. A survey of over 1000 Americans found that consumer respondents were aware of food waste issues and that they were knowledgeable about how to reduce food waste [42]. These findings suggest that many people are aware of the problem, and understand some prevention means. Therefore, it may be beneficial to target consumers with messages that treat them as already knowledgeable and engaged. Neff [42] suggests that budget-focused messages are useful because consumers may be likely to waste less if they realized how much money can be saved. The framework also emphasizes well-planned and regular outreach to stakeholders and public education, which can encourage sustained participation over time.

4.2. Inconsistent Definitions

A challenge when planning and evaluating waste management systems is the lack of clear definitions of terms. Food waste definitions are not universally agreed upon [43], which makes studying and quantifying food waste difficult [44], especially when comparing results across studies [45]. Different categorizations are made based on which materials are included and excluded, modes of production, and management endpoints [46]. Multiple terms tend to be used interchangeably, such as food loss, food waste, kitchen waste, biowaste, and food and drink waste [47], and often the same terms are used but with different meanings [46]. The framework encourages clear definition of key terms and performance indicators to address this issue. If waste data are quantified consistently between programs and the same definitions exist for waste streams, waste management systems can be accurately compared. Clear terms also facilitate the determination of performance changes over time.

4.3. Lack of Data

The lack of reliable data on food waste is a reoccurring obstacle. Poor data make it difficult to study the environmental impacts of food waste, to develop and implement sound prevention policies, and to track progress over time. This issue is widespread throughout the waste field, and poor quality or unavailable data prohibits accurate system analyses and comparisons between programs [29]. Data on waste prevention are especially scarce and/or poor [48]. A major component of the waste management framework is the establishment of methods for the collection of sufficient data on a regular basis and analyzing well-defined performance indicators. By implementing prevention campaigns with mandates for regular monitoring and evaluation, some of the existing data gaps will be resolved with time. These data can be an important resource for designing future waste prevention programs and can indicate which policy measures are the most effective.

4.4. Lack of Effective Indicators to Evaluate System Performance

The waste management framework encourages a transition away from solely using recycling or diversion rates to measure waste system performance. Shifting away from diversion-based targets may encourage waste planners to incorporate prevention initiatives and general sustainability concerns into waste management systems. A valuable indicator when examining waste prevention is the per capita disposal rate (in kilograms per person per day). Unlike a diversion rate, which may be high, though waste disposal is high, a disposal indicator tells you the amount of food waste that is being disposed after prevention and diversion. A benefit of this indicator is that is leaves less room for ambiguity or obfuscation (than the recycling or diversion rate) with regards to calculations. Recycling and diversion rates have been shown to be ambiguous, poorly defined, calculated using different formulas, and inconsistent regarding which materials are included in calculations [31]. Therefore, it is difficult to monitor progress over time using these vague indicators, and nearly impossible to compare performance from one system to another. Measuring indicators over time is a key step of the framework. Per capita rates are not affected by population changes, so they can serve as consistent measurements within a system over time, as well as across systems that differ in size and demographics.

Although the per capita disposal rate is important for system evaluations, it does not indicate the overall environmental quality or sustainability of a waste system. The waste framework encourages using performance indicators that focus on key areas of system sustainability, including issues related to environmental, economic, and social concerns, such as degree of environmental education, number of people participating in the program, amount of food redistributed to the needy, or stakeholder acceptance of waste programs. The most appropriate indicators may vary depending on local situations and waste system design [31]; the framework can help determine which indicators should be used.

4.5. Perceived High Costs

A barrier to implementing a waste prevention program is that participants may perceive prevention as costly, particularly for retailers and businesses that consider food waste to be inevitable and necessary for profit. Integrating comprehensive cost assessments, as suggested in the framework, may help address this issue. Without extensive cost analyses, it may appear beneficial in terms of labor, time, and money for restaurants to keep excess food in stock so that they never run short, even though this excess is often discarded [49]. Supermarkets keep shelves full even at the expense of throwing out excess food. Through stakeholder communication, which is an important part of the framework, managers can better understand why organizations feel food waste is inevitable and work together to reconfigure processes to reduce discards. Furthermore, sound economic analysis can be used to indicate the potential financial benefits of waste prevention. Businesses and consumers are more likely to actively prevent food waste if it is economically attractive [39]. Options include financial incentives for businesses to reduce waste, such as sustainability certification programs, which may make a business more attractive for consumers. Some consumers seek products and services that are clearly identified as sustainable, even if they are more expensive [50,51].

4.6. Little Stakeholder Engagement

There are many opportunities for meaningful partnerships to prevent food waste [52]; prevention will require specific changes from all sectors (retail, commercial, consumer, institutional) and will need strong linkages and communication among stakeholders. The European Union emphasized that tackling food waste involves working together with all stakeholders to better identify, measure, understand, and find solutions to food waste. All actors in the food chain need to collaborate to find solutions, including farmers, processors, manufacturers, retailers, and consumers, as well as technical experts, research scientists, food banks, and non-governmental organizations (NGOs). The waste management framework encourages communication among these stakeholders and the incorporation of their concerns into policy.

4.7. Uncertainty Regarding Policy Performance

Because municipal food waste management is still not universally implemented, there is a strong need to carefully analyze existing programs to determine their performance. Currently, it is unclear which food waste prevention mechanisms are most successful because evaluations of the effectiveness of the various policy options for food waste prevention are scarce, particularly because measurement of the policy impact is often not performed, especially at the local level. Because the waste framework emphasizes data collection and system evaluations, systems that utilize it can serve as key examples of what works and what does not work for food waste management. Through the integration of existing assessment models, managers can clearly determine the impacts of alternative policy options. Furthermore, a key aspect of the framework is the documentation of challenges faced when implementing policies. This information can be important when implementing similar policies elsewhere.

5. Conclusions

Effective solid waste policies and programs need to be planned carefully with consideration for diverse factors, including regulatory requirements, financial needs, environmental impacts, and social implications. The waste management framework helps ensure that these key factors are considered when managing solid waste systems and allows for the integration of multiple system assessment approaches, thus enabling benefits of each of these approaches to be obtained. Furthermore, stakeholder engagement, communication, and outreach (major aspects of the framework) are important for waste management. When the public and stakeholders are well informed about policy options, the importance of initiatives, and pathways for participation, better decisions and outcomes will result. Waste systems also need sound data collection and performance evaluation processes in place in order to allow for improvements over time. Comprehensive data collection combined with well-defined indicators is necessary. The framework is practical and affordable to implement and allows for the integration of existing waste assessment approaches, as well as local conditions. The next research priority is to apply the framework to real case studies to evaluate its actual potential for supporting solid waste management. Initial implementation of the framework should be carefully analyzed to determine exactly how it helps system performance and to identify areas where the framework may be improved.

The waste management framework fosters a holistic approach to waste management to facilitate the understanding of these complex socio-technical waste systems. In addition to enhancing waste planning and management, many of the principles defined in the framework can be leveraged in other fields to advance understanding of other complex systems. General principles of the framework that may be beneficial in other fields are the use of interdisciplinary analysis, which bridges gaps across disciplines, emphasis on stakeholder collaboration and partnerships, and effective monitoring of system performance with the ability to make system changes over time. Ultimately, the framework may serve as a key tool to improve management of municipal waste systems, and it may also have broader implications as it may encourage sustainable systems management in other fields.

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Author Contributions

The two authors worked together as a team, contributing equally to this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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