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Application of Multi-Criteria Decision Approach in the Assessment of Medical Waste Management Systems in Nigeria

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Abstract: Globally, the pandemic of COVID-19 has penetrated all spheres of human endeavors, and noteworthy is the tremendous increase in the volume of healthcare wastes generated in Nigeria. There has been an increase in medical waste materials produced as a result of the extensive use of both disposable personal protective equipment (PPE), such as face shields and nose and face masks, and highly infectious waste materials, such as contaminated syringes, needles, and soiled bandages from diagnosed positive cases. Despite the huge volume in waste generation, a standardized evaluation framework is currently lacking in the management of medical wastes in Nigeria. This study has developed a novel assessment framework for managing medical wastes, which is curated from the technical guidelines of the World Health Organization (WHO). The applicability of the framework was examined on seven designated public and private-owned hospitals in Ota. The fuzzy analytical hierarchy process (FAHP) and analytical hierarchy process (AHP) approaches of multi-criteria decision analysis were utilized in modelling an evaluation framework for the objective of medical waste management. Carefully designed interview questionnaires, observations, and site visits were carried out to obtain data from healthcare professionals in Ota. Results show that waste segregation was practiced more decisively in private hospitals than public hospitals. Waste segregation is established as a key determinant in implementing an effective waste management system in any healthcare facility. The success of waste segregation in healthcare institutions is highly dependent on good hospital management, organizational policies, efficient budget planning for waste management, and the operational running cost. Disposal methods investigated were mostly open burning and incessant dumping for most public health care centers. Deficient waste management practices were observed in waste disposal, waste transportation, storage, and organizational policies. While the awareness and capacity building on occupational safety practices and environmental public health is widely known by health workers and waste handlers, compliance and enforcement are critical challenges. The validation of results using fuzzy TOPSIS and a sensitivity analysis shows a high degree of the consistency, stability, and robustness of the model. Findings from the present study can aid decision making, as this will benefit policy makers and key stakeholders in developing more comprehensive and effective medical waste management guidelines in Nigeria. In addition, future decision-making studies could augment the results from the current research by assessing the impact of the pandemic preparedness and response on medical waste management.

Keywords: multi-criteria decision analysis (MCDA); analytical hierarchy model (AHP); fuzzy analytical hierarchy model (F-AHP); COVID-19; medical waste management (MWM); public health

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1. Introduction

As essential as health care services are, the inevitable by-product produced from health institutions requires careful management. Medical waste, otherwise called healthcare waste, comprises all waste generated at research centers, pharmaceutical centers, medical-related laboratories, and healthcare facilities, as well as waste from self-medication [1,2]. Unlike other industries, health care institutions are responsible for generating waste streams of all types, ranging from domestic to infectious to radioactive [3]. Data from the World Health Organization (WHO) show that 75–90% of the entire waste stream generated from a medical facility is domestic and non-hazardous, whereas the remaining 10–25% is deemed hazardous, infectious, or radioactive [1,2]. Hence, one of the most significant environmental issues for healthcare communities is the provision of a safe and sustainable medical waste management system [4]. Today, the emergence of COVID-19 is the principal source for the proliferation of medical wastes around the world. Nations have experienced spikes in their volume of generated medical wastes since March 2020. Remarkable advancements and breakthroughs in medical science have also led to the rapid production of medical wastes. Hence, researchers have revealed the direct and immediate impact of the COVID-19 pandemic on the environment. The production of harmful gases of sulfide and methane via open-air storage, the formation of heavy metals in landfill leachate through leaching [5], and the release of polychlorinated biphenyls and dioxins during incineration [6], which are carcinogens, are all associated with the inappropriate disposal of medical wastes [7].

The current position of medical waste management (MWM) in developing countries has become an issue of global significance. With the outbreak of the COVID-19 pandemic, we have learned how fragile medical waste management chains are and how this could lead to an increasing environmental pollution scenario [5]. As highlighted by C. Sonne, S. You, and Y. S. Ok [5], there has been an upsurge in medical waste created from diagnosed positive cases. The highly contagious nature of COVID-19 makes medical waste management vital to public health [6]. At this current state of the pandemic, many developing countries face medical waste management challenges, particularly regarding the generation, collection, and disposal of COVID-related waste. Globally, there are limitations in assessing the current status of medical waste management, as a standardized evaluation framework is lacking in most countries [4]. International public health agencies, such as the World Health Organization, have issued technical guidelines and reports on the safe management of wastes from healthcare activities for developing countries [1,2]. However, there is a need to effectively understand the current medical waste management practices in specifics, as it applies to different countries in determining the effectiveness of such guidelines.

In addressing this gap, this study will employ the analytical hierarchy process (AHP) and the fuzzy analytical hierarchy process (FAHP) of the multi-criteria decision analysis (MCDA). These methodologies are applied to evaluate criteria based on WHO technical guidelines for MWM, providing an in-depth and comprehensive evaluation framework in assessing the status of waste management of hospitals in Ota, which is known to be the most industrialized town in Ogun State [7]. Ota was selected because it houses the highest healthcare institutions in the state [8], and thus large volumes of medical wastes are produced daily. This research responds to the gap of developing an appraisal framework for determining the efficiency of the existing medical waste management systems in emerging countries, especially Nigeria. Generally, medical waste is often used synonymously as healthcare waste, clinical waste, hospital waste, pharmaceutical waste, biomedical or biohazardous waste, and infectious waste across the globe, but for this study, "medical waste" will be adopted and used.

This paper broadens the scope of medical waste management and the sustainable inclusion of decision-making tools in effective waste management. First, we identify essential criteria for the assessment of medical waste management in a hospital. Second, we develop a hierarchical model based on the identified criteria with effective medical waste management as the goal and alternatives (hospitals). Third, we carefully design interview questionnaires, observations, and conduct site visits to obtain data from experts and healthcare workers in Ota. Then, we apply the MCDA-based approach of AHP and fuzzy AHP to the real-life scenario of hospital waste management in the Nigerian context. Finally, we compare obtained rankings from the methodologies to evaluate each criterion against health facilities. Lastly, the study highlights the implication of MWM on health workers and the general public. The remainder of the paper is organized as follows:

the next section discusses the state of medical waste management in Nigeria. Then, we provide details on the MCDA methodologies (AHP and fuzzy AHP) selected for this study, followed by the ethical evaluation. We finalize by discussing our results, the implications for health workers and society, and then the conclusion.

2. Medical Waste Challenges in Nigeria

Nigeria, officially termed the Federal Republic of Nigeria, is the largest country in West Africa and the most populous nation in Africa, covering a total land size of 923,769 sq.km. According to Worldometer, Nigeria's population is estimated at 211 million [9], and, at this current growth rate, the country's population is expected to exceed the United States by 2050 [10]. Nigeria shares a border with Chad, Cameroon, Niger, Benin, the Gulf of Guinea, and the Atlantic Ocean. The country's economy is predominantly crude oil mining, but with the recent plummet of prices of crude oil internationally, the nation has heightened focus on agriculture, entrepreneurship, and the mining of other natural resources. Despite recent improvements, the country faces challenges in providing adequate basic amenities and services, such as access to potable water, constant electricity, good living standards, basic health care facilities, acceptable industrial pollution emission [11], and effective waste management systems. The issue of waste management across all sectors has become a major problem in Nigeria. Solid waste management in Nigeria has been a persisting challenge because of the ever-growing population [12]. World Bank estimates that the Sub-Saharan region of Africa generates approximately 174 million tonnes of waste per annum, with prominent leaders from middle-income countries and tourist nations [13]. The rate of waste generation in Nigeria is estimated at 0.65–0.95 kg/capita/day and the scenario in the nation's commercial hub, Lagos, is 0.5 kg/capita/day [14,15]. This estimation gives the average volume of generated waste as 42 million tonnes per annum [14]. Studies in Nigeria have projected the medical waste generation to be between 0.562–0.670 kg/bed/day, with a peak rate of 1.68 kg/bed/day [16]. Similarly, rates of 0.631 kg/bed/day are estimated for areas in the Lagos and Ikorodu metropolis [17].

Poor awareness, inadequate knowledge, and the management of medical wastes in Nigeria have given credence to classifying medical wastes as municipal solid wastes [17]. It is estimated that several tonnes of unrecorded medical waste have been disposed of in open dumps and pits, further mixed with domestic solid wastes. The outbreak of nosocomial diseases in Nigeria is predominately linked to poor medical waste management [18,19]. Hence, there is a need to promptly address the challenge of medical waste management appropriately. In Nigeria, the National Environmental Standards and Regulations Enforcement Agency (NESREA) classifies healthcare wastes into 10 classifications, which include; general solid waste, infectious waste, heavy metals waste, genotoxic waste, microorganisms, pathological waste, pressurized containers, sharps, chemical waste, and pharmaceutical waste [20]. Contrastingly, the Nigeria Healthcare Waste Management Guideline of 2013 by the Federal Ministry of Health categorizes healthcare wastes into eight classifications, namely: non-hazardous or general wastes, pathological/anatomical waste, mercury wastes, infectious wastes, chemical/pharmaceutical/genotoxic wastes, sharps, radioactive wastes, and highly infectious wastes [21]. The classification of these wastes does not entail its management from source to sink, as there is no legislative monitoring or assessment compliance by health facilities within the country. Hence, the current position and classification of medical waste in Nigeria varies greatly among its regulatory agencies. This has resulted in poor monitoring, a lack of strict compliance, and disparate disposal activities by medical facilities. As of today, there is no legal framework or legislation on medical waste management in Nigeria. However, through its collaboration with other public health agencies, the Federal Ministry of Health has provided the following documents on healthcare waste management; National Healthcare Waste Management Guidelines, National Healthcare Waste Management Policy, and the National Healthcare Waste Management Plan [21]. Despite the above documents, the compliance evaluation by regulatory agencies on health care facilities is poor and non-existent, as there is no standardized evaluation framework for medical waste management based on any legislation in Nigeria. Additional constraints of medical waste management in Nigeria include poor or lack of segregation of medical waste at the point of generation, a deficient or non-existent recommended medical waste color–coding or labelling system, inadequate personal protective equipment (PPE) for waste handlers, inadequate medical waste management information for health workers and waste handlers, and the incessant dumping of medical waste into municipal dumpsites.

3. Methodology

There are limitations in assessing the current status of medical waste management, as a standardized evaluation framework is currently lacking in most countries [4]. Global community health, such as the World Health Organization, have issued technical guidelines and reports on the safe management of wastes from healthcare activities for developing countries [1,2]. However, the current hospital waste management practices are not assessed by these guidelines to determine effectiveness, compliance, and applicability to various countries" regulations. In addressing this gap, this study will employ the multi-criteria decision analysis (MCDA) approach with evaluation criteria, based on WHO technical guidelines for MWM, to provide an in-depth and comprehensive evaluation framework in assessing the current status of waste management in hospitals. Two hundred and fifty-seven questionnaires were provided to health workers and waste handlers, where information obtained was analyzed using MCDA. Multi-criteria decision analysis is often described as an approach or set of techniques that is vastly applied in various fields as an instrument for evaluating options in decisions involving numerous often contradictory criteria, pre-defined constraints, and stakeholders' opinions [22]. MCDA was first applied in the area of operations research, but over the years, MCDA has become of great interest to other disciplines. It is widely used in resource allocation [23], telecommunication [24,25], waste management [26], marketing [27], healthcare [28], energy planning [29], manufacturing [30], business decision [31], and budgeting [32]. Inadequate economies and analytical deficiencies of previous studies on medical waste management have prompted the use of an integrated evaluation framework known as the multi-criteria decision analysis (MCDA) in recent years [4]. In proffering solutions to the challenges of municipal waste management, Tseng (2009) effectively applied the decision-making trial and evaluation laboratory (DEMATEL) and analytic network process (ANP) methods in Manila [33]. Furthermore, Romero and Carnero also applied AHP in determining the environmental evaluation of health care organizations in Spain [3]. In Japan, Babalola revealed opportunities and usability in the food waste management chains using the AHP procedures [34]. Manupati et al. (2021), in his paper, utilized the fuzzy VIKOR method in comparison with the fuzzy TOPSIS (technique of order preference similarity to the ideal solution) in assessing a framework for the determination of the best healthcare waste disposal technique based on triple bottom line perspectives and socio-technical criteria [6]. Aghapour et al. (2013) presented the healthcare waste management index as an instrument to aggregate the various scores of diverse waste management phases into a sole figure. The stage includes collection, storage, segregation, transportation, treatment, and disposal [35]. Carnero (2015) combined the utility theory and the fuzzy analytic hierarchy process to assess environmental sustainability in health care organizations (HCOs) [36]. In the University Regional General Hospital of Patras, Western Greece, Zamparas (2019) introduced the analytic hierarchy process (AHP) methodology, which was used to determine the present methods and techniques in handling and managing infectious wastes in its largest health care unit [37]. In Myanmar, Aung (2019) applied MCDA techniques to analyze medical waste management using evaluation criteria of segregation, treatment and disposal, capacity building, safety practices for waste handling personnel, waste transportation, and waste collection and storage [4]. Consequently, for this study, evaluation criteria are further broadened into environmental public health and occupational safety practices, staff awareness, organizational policy, and management plan criteria. In addition, over the past decades, several researchers have assessed MWM in various nations. Komilis et al. (2012) estimated the production rate of hazardous medical wastes in Greece. Nguyen and Nguyen (2014) calculated the trend and future production rate of solid medical wastes in Vietnam [38]. In Iran, Farzadkia (2015) investigated the solid hospital waste management [39]. Other studies have based their analysis on the generation rate of on-site wastes [38–40]. In investigating the medical waste management structure of a health facility, a common method that involves the various stages of MWM, such as collection, generation, disposal, segregation, storage, transportation, and training as observable variables, is mostly preferred [35,41,42]. Questionnaires, observations, inspection surveys, interviews, and site visits are utilized by researchers to gather data for the various stages of MWM [4]. Notwithstanding the general scientific evaluation of waste management in health institutions, an inclusive and uniform assessment framework to evaluate the position of medical waste management is presently deficient, as decision makers ignore the inclusive framework of analysis; for example, the views of local experts and the opinions of key stakeholders.

In developing an assessment framework for medical waste management, the goal and the criteria must be defined, as shown in Table 1. In this study, the evaluation criteria are based on WHO technical guidelines for MWM. The main objective is to assess medical waste management systems in Ota, thereby providing an in-depth and comprehensive evaluation framework for the selected hospitals. The criteria identified include: waste segregation (M1), waste collection and storage (M2), waste transportation (M3), waste treatment (M4), waste disposal (M5), environmental public health/occupational safety practices (M6), awareness/capacity building (M7), organizational policy/management plan (M8), and budget/operational cost (M9). The nine criteria were selected with relevance to the Nigerian context. The attributes represent the analysis of the evaluated criteria as they fulfil the WHO standard. Validated questionnaires ($n = 257$) were administered to randomly selected healthcare workers from selected private and public hospitals between February and April 2021. A total of 275 healthcare workers and medical waste handlers were administered validated questionnaires, out of which 257 questionnaires were recovered (response rate = 93.45%). The study participants ($n = 257$) were administered personally to healthcare workers and medical waste handlers, consisting of 106 nurses, 43 doctors, 6 waste handlers, 35 medical laboratory scientists, 8 X-ray technicians, and 59 other health workers from selected private and public hospitals.

Table 1. AHP goal and criteria description.

Goal: Assessment of Medical Waste Management Systems in Ota		
Serial Number	**Criterion**	**Attributes**
M1	Waste Segregation	This measures the efficiency of waste segregation into their different categories during waste generation in a particular medical facility. Health workers can identify each waste based on its potential hazard, and disposal is into the recommended color-coded containers.
M2	Budget/Operational Cost	This measures the total budget and operating cost involved per year in operating and maintaining a particular medical facility.
M3	Waste Treatment	This analyses the type and amount of waste that can be treated by each medical facility in a particular cycle of operation and the different treatment methods available. Are sharps autoclaved, shredded, or captured in cement?

Table 1. *Cont.*

Goal: Assessment of Medical Waste Management Systems in Ota		
Serial Number	**Criterion**	**Attributes**
M4	Waste Transportation	This analyzes the various approaches by which medical waste is transported from facilities to treatment and disposal sites. Is the transportation time for medical waste fixed? How compliant are waste handlers when transporting and managing medical waste?
M5	Waste Disposal	This measures the various disposal methods of medical waste, their disposal sites, and the closeness of the disposal site to a medical facility.
M6	Environmental Public Health/Occupational Safety Practices	This analyzes the environmental degrading toxic emissions associated with each medical facility and the dangerous health effects on health workers and the immediate surroundings. It further examines the requirement of various safety procedures and risks associated with operating a particular medical facility. Prevention against nosocomial infections. Documentation of incidents and accidents during medical operations and waste handling. Are health workers immunized against potentially infectious diseases?
M7	Awareness/Capacity Building	This measures the occupational awareness of health workers and professionals to medical waste management and the aptitude of each facility to develop its workers. How often are health workers trained on managing emerging infections?
M8	Organizational Policy/Management Plan	This analyzes the operational structure of medical waste management available in each facility. It measures the implementation of internal regulations and the national policy of medical waste management. Is there a health, safety, and environmental officer in charge of managing, monitoring, and enforcing the best waste management practices within each facility?
M9	Waste Collection and Storage	This measure covers the different types of waste collection and storage methods available for various categories of medical waste, storage time, and collection procedures. Containers are correctly labelled. Medical waste bins are filled to no more than $\frac{3}{4}$ full.

This study has triangulated relevant published literatures, international and national regulations, governmental and non-governmental guidelines, and health expert opinions to understand and bring relevance to the Nigerian context. A panel of local experts were responsible for defining the importance score of each criterion. The local expert is either a medical professional in the selected hospital holding a senior management position or a public health worker with over 15 years of working experience. The local experts are knowledgeable about the medical waste management practices in Nigeria. The aggregated score for each criterion was obtained from the consensus of 7 local experts from the selected hospitals. Figure 1 and Table 2 show the selected hospitals and their summary, respectively. Table 3 presents the description of selected health facilities. Furthermore, methodologies of AHP and fuzzy AHP are validated with fuzzy TOPSIS and the sensitivity analysis.

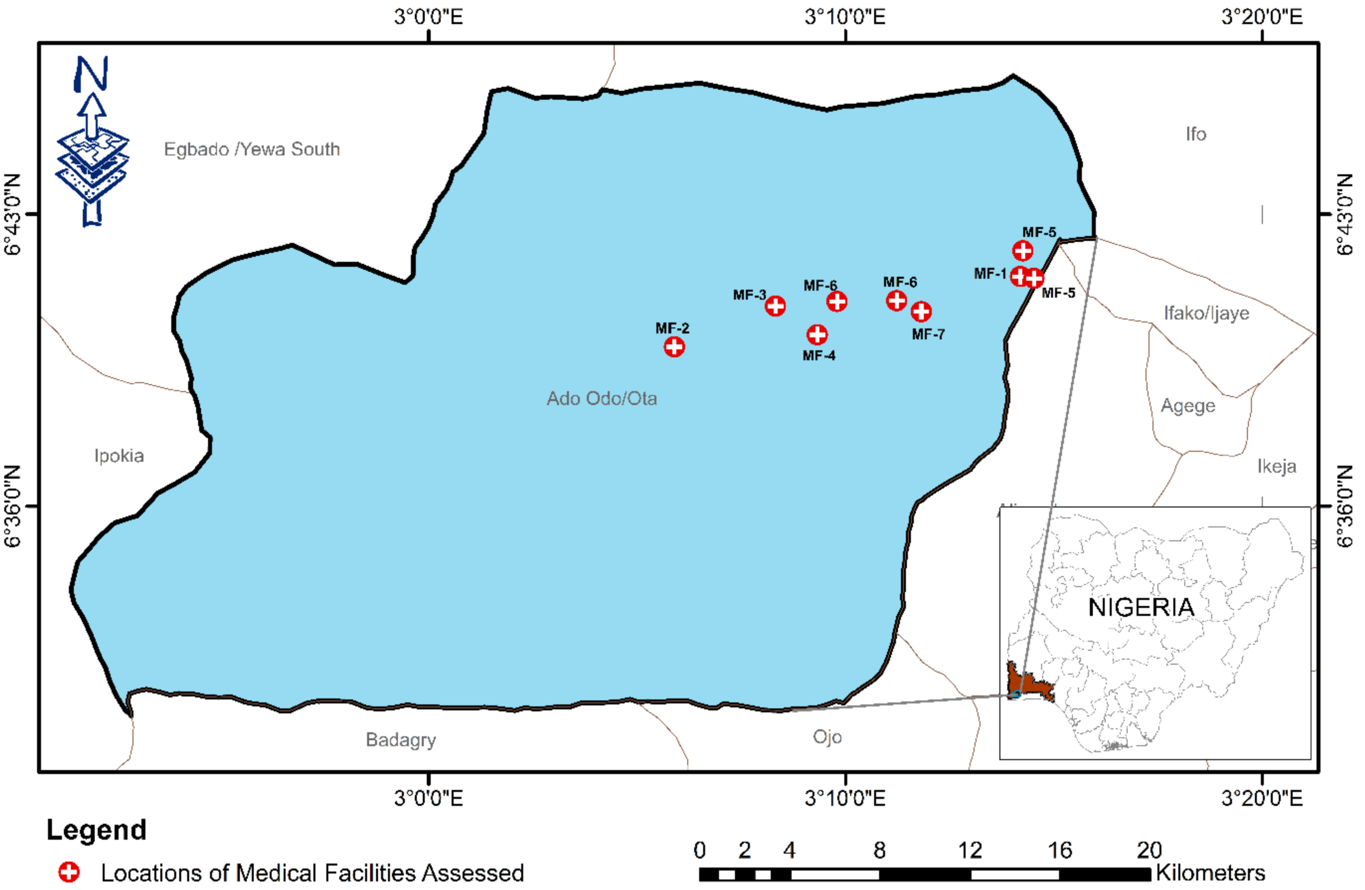

Figure 1. Map of Ado-Odo/Ota showing the selected health care centers.

Table 2. Summary of selected hospitals.

Medical Facility (MF)	Hospital Type		Facility Level		
	Private	Public	Primary	Secondary	Tertiary
MF–1: H5		×	×		
MF–2: H6		×	×		
MF–3: H7		×	×		
MF–4: H4	×			×	
MF–5: H2	×			×	
MF–6: H1	×			×	
MF–7: H3	×			×	

Table 3. Description of selected health facilities.

S/N	Health Institution	Description	Services Rendered	No. of Beds	No. of Health Workers	Location
1	H5	Largest public health center in Ota, publicly owned	Outpatient services, infant care and immunization services, family planning, ante-natal planning, post-natal planning, maternity, pharmaceutical services, XYZ session, eye clinic, laboratory services.	7	29	Ota
2	H2	Privately owned	24-h general outpatient clinic services and in-patient care, 24-h emergency and ambulance services, antenatal clinic, post-natal care, dental clinic, laboratory services, public health services such as family planning and immunization, pharmaceutical services, visual care services, general surgical services, diagnostic imaging and radiology, pediatrics, maternity services.	26	55	Ota

Table 3. *Cont.*

S/N	Health Institution	Description	Services Rendered	No. of Beds	No. of Health Workers	Location
3	H6	Largest primary health center in Atan, publicly owned	24-h general outpatient clinic services and in-patient care, antenatal clinic, post-natal care, laboratory services, public health services such as family planning and immunization, pharmaceutical services, maternity services.	4	8	Atan
4	H7	Largest primary health center in Iju, publicly owned	24-h general outpatient clinic services and in-patient care, antenatal clinic, post-natal care, public health services such as family planning and immunization, pharmaceutical services, maternity services.	4	7	Iju
5	H3	Privately owned	24-h general outpatient clinic services and in-patient care, 24-h emergency and ambulance services, antenatal clinic, post-natal care, dental clinic, laboratory services, pharmaceutical services, general surgical services, physiotherapy, diagnostic imaging and radiology, maternity services, orthopedic services.	29	24	Ota
6	H1	Largest privately-owned hospital in Ota	24-h general outpatient clinic services and in-patient care, 24-h emergency and ambulance services, antenatal clinic, post-natal care, dental clinic, laboratory services, public health services such as family planning and immunization, pharmaceutical services, visual care services, general surgical services, physiotherapy, intensive care unit (ICU) or intensive treatment unit (ITU), diagnostic imaging and radiology, internal medicine (gastroenterology, cardiology, nephrology, pulmonology, etc.), pediatrics, maternity services.	36	75	Ota
7	H4	Institutional and privately owned hospital	24-h general outpatient clinic services and in-patient care, 24-h emergency and ambulance services, antenatal clinic, post-natal care, dental clinic, laboratory services, public health services such as family planning and immunization, pharmaceutical services, visual care services, general surgical services, physiotherapy, diagnostic imaging and radiology, pediatrics, maternity services.	50	77	Ota

3.1. Multi-Criteria Decision Analysis

Among the different MCDA approaches, the analytic hierarchy process (AHP) is a well-defined methodology developed by Saaty [43] that has been greatly used in selecting waste management treatment and disposal technologies, particularly in the healthcare industry. The model allows health professional decision makers to detect flaws and strengths in various hospitals' healthcare waste management [4]. AHP methodology grants decision makers the ability to break down a complex problem into sets of criteria, sub-criteria, and alternatives based on experts' preferences, as shown in Figure 2. Due to its simplicity and ease of use, this approach is widely used. Decision makers prefer AHP and its extensive use in literature. Just like most MCDM techniques (TOPSIS, ELECTRE, MAUT), the issue of rank reversal is common [44–46]. This is a difficult issue and may not currently be answered in a globally acceptable way. Therefore, in this study, to ensure the validity of our results, derived rankings were applied in context and with past literatures. The unique application of the analytic hierarchy process includes [47]:

- Resource assignment
- Choice
- Market comparison
- Prioritization
- Quality control

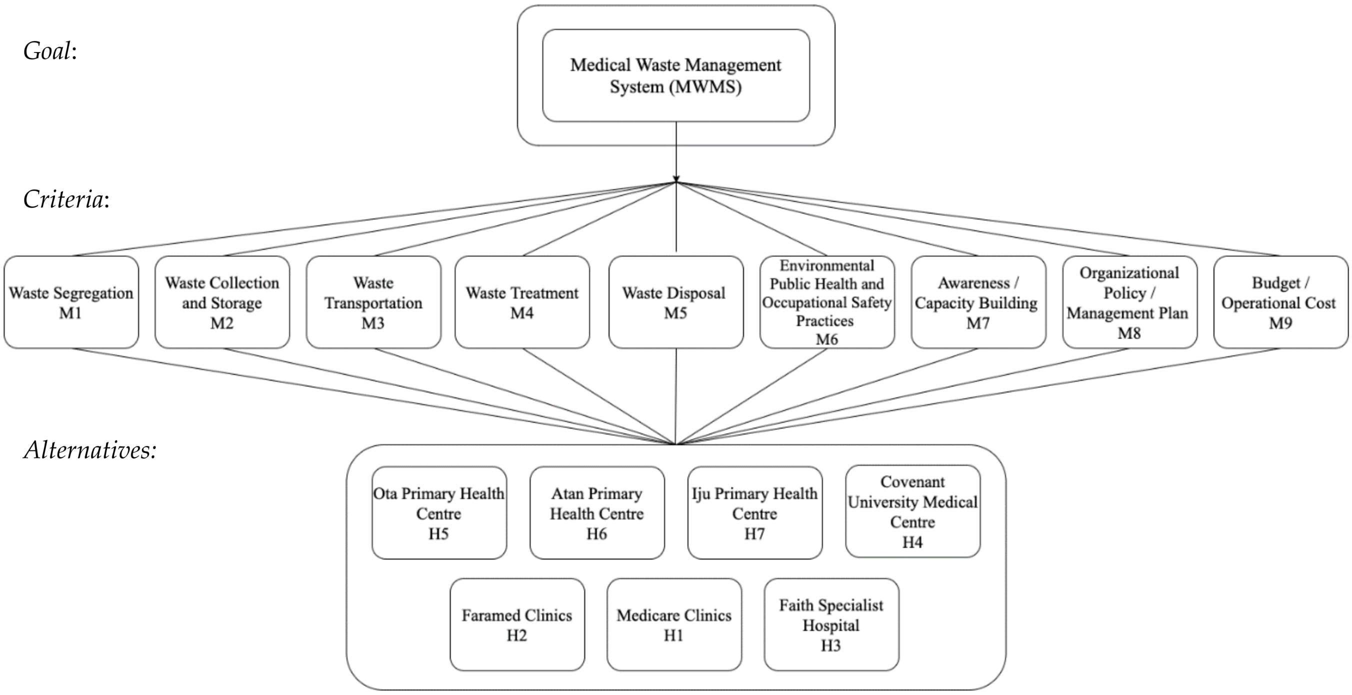

Figure 2. The AHP decision hierarchy model.

The AHP model is defined by a goal, set of criteria, and sub-criteria, analyzed for the importance and relevance to the goal and alternatives. Their pairwise comparison is also determined based on experts' judgments. The goal, criteria, and alternatives are elements of the decision problem in the model development. AHP development comprises the following steps [43]:

The problem is structures at the hierarchy's highest level, followed by criteria, sub-criteria, and existing alternatives at the lowermost level. Criteria weights are obtained through the following equations below. The n criteria in a similar stage are compared with Saaty's 1-to-9 scale of comparison (Table 4), and pairwise comparison matrix A is obtained for each level based on the professionals' decision a_{ij}.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix}, \text{ where } a_{ji} = 1/a_{ij} \; i, j = 1, \cdots, n \tag{1}$$

Table 4. Scale for pairwise comparisons.

Relative Intensity	Definition	Description
1	Equal value	Two criteria are of equal value
3	Slightly greater value	Slightly favors one criterion over another
5	Essential or strong value	Strongly favors one criterion over another
7	Very strong value	A criterion is strongly favored, and its dominance is demonstrated in practice
9	Extreme value	Highest possible order of affirmation and evidence favoring one over another
2, 4, 6, 8	Intermediate values between two adjacent judgements	When conciliation is required
Reciprocals	Reciprocals for inverse comparison	

Comparison matrix and B column vector are used in developing the weight of the criteria.

$$B = \begin{bmatrix} b_{11} \\ b_{21} \\ \vdots \\ b_{n1} \end{bmatrix} \quad (2)$$

The vector of B column is obtained via the formula:

$$b_{ij} = \frac{a_{ij}}{\sum_i^n a_{ij}} \quad (3)$$

The combination of n number of B column vectors is given in matrix C below:

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} \quad (4)$$

The priority vector or matrix W or percentage importance distribution is derived below:

$$w_i = \frac{\sum_{j=1}^{n} c_{ij}}{n} \quad (5)$$

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad (6)$$

In determining any decision-making inconsistencies, the consistency ratio (CR) of matrix A is employed:

$$CR = \frac{CI}{RI} \quad (7)$$

where $CI = \frac{\lambda_{max} - n}{n-1}$ and λ_{max} is the maximal eigenvalue of A.

The consistency index (CI) is dependent on the maximal eigenvalue, and the random index, RI, or experimental value is dependent on the number of criteria selected. For the consistency ratio to be less than the threshold value, a matrix is considered consistent, and values from the matrix are meaningful. The random index values in Table 5 are 0.58 for $n = 3$, 0.9 for $n = 4$, and 1.0 for $n \geq 5$. The priorities vector, $P = (P_1, P_2, P_i \ldots P_n)$, was obtained from the pairwise comparison matrix A, after which global priorities were synthesized from the local priorities, where gi, $i = 1, \ldots, n^H$, where n^H is the number of criteria and sub-criteria in the hierarchy. The total of all global priorities is 1. For each criterion, the alternative evaluation was obtained through rating. Hence, the decision matrix was constructed using the priorities of the criteria and alternatives obtained. Using an MCDA method via the weighted sum model, the alternative priorities and criteria priorities were summed up.

Table 5. Random index of analytic hierarchy process.

Size of matrix	1	2	3	4	5	6	7	8	9	10	11	12
Random index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.58

Furthermore, fuzzy set theory considers vagueness, uncertainty, and ambiguous situations of experts' judgement and decision making [48]. The fuzzy AHP model will be employed in this research. It is designed to consider the varying degree of vagueness in the selected parameters, making decision makers more poised about their judgments rather than single value judgments. The triangular fuzzy number is well-defined by $\widetilde{a} = (l, m, u)$, where l = lower limit, u = upper limit, and u is the point where function $\mu_{\widetilde{a}}(x) = 1$, $\widetilde{a}$ is defined by the membership function $\mu_a(x) : \Re \rightarrow [0,\ 1]$ according to Equation (8)

$$\mu_a(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l}, & x \in [l,\ m] \\ \frac{x}{m-u} - \frac{u}{m-u}, & x \in [m,\ u] \\ 0, & otherwise \end{cases} \quad (8)$$

with $l \leq m \leq u; if\ l = m = u$, then the fuzzy number becomes a crisp number by convention. The operational laws of two fuzzy triangular numbers $\tilde{a}_1 = (l_1, m_1, u_1)\ and$ $\tilde{a}_2 = (l_2, m_2, u_2)$ are the following:

$$\tilde{a}_1 \bigoplus \tilde{a}_2 = (l_1 + l_1,\ m_1 + m_2,\ u_1,\ u_1 + u_2) \quad (9)$$

$$\tilde{a}_1 \Theta\ \tilde{a}_2 = (l_1 + u_2,\ m_1 - m_2,\ u_1,\ u_1 + l_2) \quad (10)$$

$$\tilde{a}_1 \bigotimes \tilde{a}_2 \approx ((l_1 l_2, m_1 m_2, u_1 u_2) \quad (11)$$

$$\tilde{a}_1 \Phi\ \tilde{a}_2 \approx \left(\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{u_1}{l_2} \right) \quad (12)$$

$$\tilde{a}_1{}^{-1} \approx \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1} \right) for\ l, m, u > 0 \quad (13)$$

$$k \bigotimes\ \tilde{a}_1 \approx (kl_1, km_1, ku_1)\ k > 0,\ k \in R \quad (14)$$

From the fuzzy judgements' matrix Ã, the scale levels for each indicator and the weightings of the criteria are obtained. The matrix has an element of fuzzy comparison values $\widetilde{a}_{ij}$ which expresses the decision maker's assessment about the relative importance of element i over element j at the same level in the hierarchy [48,49].

$$A = \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \ldots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \ldots & \tilde{a}_{2n} \\ \vdots & \vdots & \ldots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \ldots & (1,1,1) \end{bmatrix} \quad (15)$$

To perform a pairwise comparison of matrix Ã, the decision maker utilizes the fuzzy linguistic scale in Table 6. The scale is selected and preferred because it agrees with the original scale of preference of AHP established by Saaty in 1980.

Table 6. Fuzzy linguistic scale.

Linguistic Scale	Fuzzy Number	Triangular Fuzzy Numbers	Triangular Fuzzy Reciprocal Numbers
Equally important	$\widetilde{1}$	(1, 1, 1)	(1, 1, 1)
Judgement values between equally and moderately	$\widetilde{2}$	(1, 2, 3)	(1/3, 1/2, 1)
Moderately more important	$\widetilde{3}$	(2, 3, 4)	(1/4, 1/3, 1/2)
Judgement values between moderately and strongly	$\widetilde{4}$	(3, 4, 5)	(1/5, 1/4, 1/3)
Strongly more important	$\widetilde{5}$	(4, 5, 6)	(1/6, 1/5, 1/4)
Judgement values between strongly and very strongly	$\widetilde{6}$	(5, 6, 7)	(1/7, 1/6, 1/5)
Very strongly more important	$\widetilde{7}$	(6, 7, 8)	(1/8, 1/7, 1/6)
Judgement values between very strongly and extremely	$\widetilde{8}$	(7, 8, 9)	(1/9, 1/8,/7)
Extremely more important	$\widetilde{9}$	(8, 9, 9)	(1/9, 1/9, 1/8)

To obtain a pairwise comparison matrix for the decision criteria and sub-criteria, a local health professional is consulted. The decision maker was asked to evaluate the importance of the criteria and sub-criteria applying the fuzzy scale set; the result was the pairwise comparison matrix for the criteria. Next, the value of the fuzzy synthetic extent with respect to the *i*-object $\widetilde{S}$ is obtained; this is carried out by applying Equation (16) [36].

$$\widetilde{S}_i = \sum_{j=1}^{m} \widetilde{a}_{ij} \bigotimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} \widetilde{a}_{ij}\right]^{-1} \quad (16)$$

where $\widetilde{a}_{ij}$ is a triangular fuzzy number of the decision matrix $\widetilde{A}$, with n-objects and m-goals.

$$\left(\sum_{i=1}^{n}\sum_{j=1}^{m} \widetilde{a}_{ij})^{-1} = (\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} u_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} m_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} l_{ij}}\right) \quad (17)$$

The values of fuzzy synthetic extents are compared and the degree of possibility of $V\left(\widetilde{S}_j \geq \widetilde{S}_i\right)$ is calculated using Equation (18) [36].

$$V\left(\widetilde{S}_j \geq \widetilde{S}_i\right) = height\left(\widetilde{S}_i \cap \widetilde{S}_i\right) = \begin{cases} 1, & if\ m_j \geq m_i \\ 0, & if\ l_i \geq u_j \\ \frac{l_i - u_j}{(m_j - u_j) - (m_i - l_i)}, & otherwise \end{cases} \quad (18)$$

It is crucial to determine the consistency of the judgement made by experts to guarantee thorough randomness. Hence, consistency index (*CI*) is determined to evaluate the deviations from consistency in the judgements, as obtained from the formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (19)$$

The consistency ratio (*CR*) is obtained from the equation below. The random consistency index (*RCI*) is produced by a random matrix of a similar dimension to that computed and evaluated by Saaty.

$$CR = \frac{CI}{RCI} \quad (20)$$

3.2. Ethical Consideration

With reference to the US Dept. of Health and Human Services (IORG0010037), study approval for this research proposal procedure was secured from the Covenant University Health Research Ethics Committee, Ota, with an HREC Protocol Assigned Number of CHREC/065/2021. The researcher is certified with the Nigerian National Code for Health Research Ethics; Record ID: 40882926.

4. Results and Discussion

The following sub-sections explicitly discuss the results obtained from the analysis.

4.1. The Results of the Analytical Hierarchy Process (AHP)

The first objective of this study was to develop an analytical hierarchy process (AHP) model for analyzing medical waste management in selected hospitals in Ota. The process is designed into levels of structured criteria, which are; waste segregation (M1), budget/operational cost (M2), waste treatment (M3), waste transportation (M4), waste disposal (M5), environmental public health/occupational safety practices (M6), awareness/capacity building (M7), organizational policy/management plan (M8), and waste collection and storage (M9). The selected hospitals are then put as alternatives in the final phase of the model creation and analyzed against each criterion in achieving the model's objective. The AHP model allows experts to decompose complex problems into a hierarchy of goal, criteria, and alternatives based on the decision makers. An extensive pairwise comparison is presented in Table 7, showing a hierarchy of nine sets of paired comparisons. The results are described in integer values, from 1, which represents an equal value, to 9, which represents different extreme values. A higher number means that the chosen criteria are considered more important to a greater degree than other criteria.

Table 7. Pairwise comparison matrix.

Criteria	M1	M2	M3	M4	M5	M6	M7	M8	M9
M1	1.0000	2.0000	3.0000	3.0000	1.0000	2.0000	1.0000	3.0000	1.0000
M2	0.5000	1.0000	3.0000	1.0000	1.0000	0.3333	1.0000	2.0000	2.0000
M3	0.3333	0.3333	1.0000	2.0000	0.3333	1.0000	1.0000	1.0000	1.0000
M4	0.3333	1.0000	0.5000	1.0000	1.0000	0.3333	0.3333	0.3333	2.0000
M5	1.0000	1.0000	3.0000	1.0000	1.0000	3.0000	1.0000	1.0000	2.0000
M6	0.5000	3.0000	1.0000	3.0000	0.3333	1.0000	3.0000	2.0000	2.0000
M7	1.0000	1.0000	1.0000	3.0000	1.0000	0.3333	1.0000	2.0000	1.0000
M8	0.3333	0.5000	1.0000	3.0000	1.0000	0.5000	0.5000	1.0000	2.0000
M9	1.0000	0.5000	1.0000	0.5000	0.5000	0.5000	1.0000	0.5000	1.0000

The consistency ratio (CR) of the above matrix is used to check for any discrepancies in the given observations using Equations (19) and (20). The random index is an experimental value that is dependent on the number of criteria assessed. The synthesis results of the AHP model are presented in Table 8.

$$CI = \frac{10.1441 - 9}{9 - 1} = 0.1430$$

$$CR = \frac{0.1430}{1.45} = 0.098 < 0.1\ (Acceptable)$$

Table 8. Synthesis results of the AHP model.

Criteria	Weighted Sum Value	Criteria Weight	$\lambda_{\max}$ Average
M1	1.7361	0.1674	10.3667
M2	1.1278	0.1134	9.9400
M3	0.7840	0.07552	10.3803
M4	0.6861	0.0692	9.9072
M5	1.5289	0.1469	10.4022
M6	1.5703	0.1528	10.2751
M7	1.1267	0.1121	10.0464
M8	0.9099	0.0901	10.0964
M9	0.7137	0.0722	9.8817
λ_{max}			10.144

The inter-relationship between the criteria in the matrix is shown in the chord diagram, as illustrated in Figure 3. This shows the connection and flow of all criteria used in the assessment of medical waste management and their respective significance to each other. The interlink of one criterion to another describes the importance of all selected criteria in implementing an effective medical waste management system in hospitals. Large dependencies are observed in waste segregation, environmental public health/occupational safety practices, awareness/capacity building, and the organizational policy/management plan. These criteria are crucial in any waste management system. The size and width of the arc are proportional to the importance of the flow.

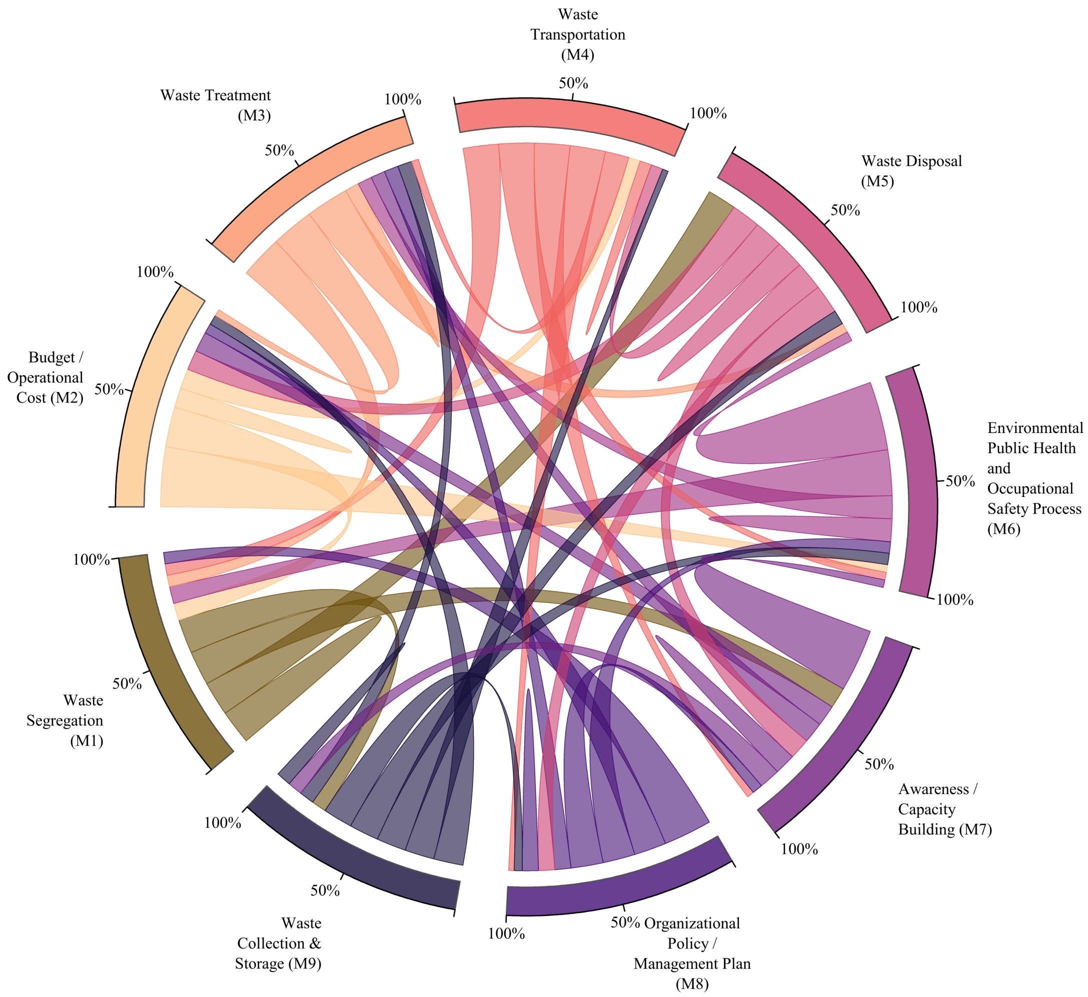

Figure 3. Chord diagram showing the inter-relationships between criteria.

Table 9 highlights waste segregation and waste collection and storage as the highest (16.75%) and the least priority (7.22%), respectively, in achieving an effective waste management in health care institutions. The success of waste segregation is crucial across all other criteria. The priorities by alternatives show the performance ratings of each hospital with their corresponding criterion index. Figure 4 illustrates the relative percentage rating of all selected hospitals as alternatives against each criterion.

Table 9. Normalized pairwise comparison matrix.

	M1	M2	M3	M4	M5	M6	M7	M8	M9	Criteria Weight	Weighted Sum
M1	0.1667	0.1935	0.2069	0.1714	0.1395	0.2222	0.1017	0.2338	0.0714	0.1675	1.7361
M2	0.0833	0.0968	0.2069	0.0571	0.1395	0.0370	0.1017	0.1558	0.1429	0.1135	1.1278
M3	0.0556	0.0323	0.0690	0.1143	0.0465	0.1111	0.1017	0.0779	0.0714	0.0755	0.7840
M4	0.0556	0.0968	0.0345	0.0571	0.1395	0.0370	0.0339	0.0260	0.1429	0.0693	0.6861
M5	0.1667	0.0968	0.2069	0.0571	0.1395	0.3333	0.1017	0.0779	0.1429	0.1470	1.5289
M6	0.0833	0.2903	0.0690	0.1714	0.0465	0.1111	0.3051	0.1558	0.1429	0.1528	1.5703
M7	0.1667	0.0968	0.0690	0.1714	0.1395	0.0370	0.1017	0.1558	0.0714	0.1122	1.1267
M8	0.0556	0.0484	0.0690	0.1714	0.1395	0.0556	0.0508	0.0779	0.1429	0.0901	0.9099
M9	0.1667	0.0484	0.0690	0.0286	0.0698	0.0556	0.1017	0.0390	0.0714	0.0722	0.7137
∑										1	9

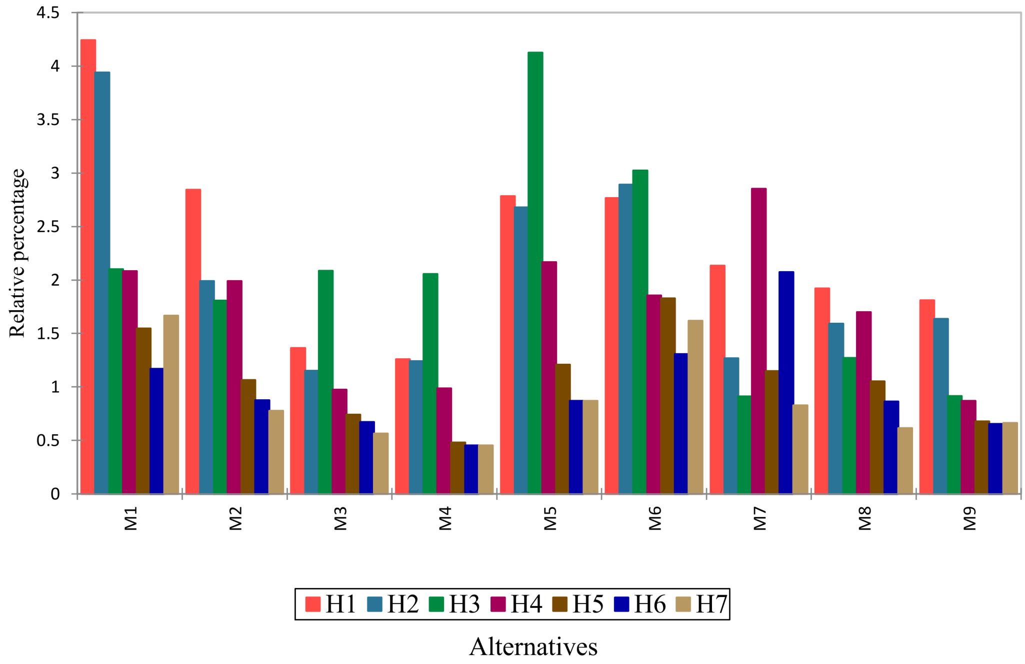

Figure 4. Priorities by alternative.

From the analysis, the results of the consistency index (CI) and coherence ratio (RC) of the matrix were 0.1430 and 0.0986, respectively, which is within the tolerable level of inconsistency of <10% postulated by Saaty, 1980. From the analytical hierarchy process analysis, waste segregation (M1) has the highest weight and is considered the most vital criteria for medical waste management in Ota. This supports the standpoint of a recent research in Myanmar that reports segregation as the foremost criteria in accomplishing a successful medical waste management process [1,4]. The magnitude of relative intensities for waste segregation is more significant compared with other parameters, making the attainment of others reliant on it. Proper medical waste segregation thrives when the health workforce is informed through capacity building engagements coupled with the right organizational management plan to ensure enforcement. This is the basis for ensuring a higher performance in infection control [1]. For developing countries, inadequate or lack of training and the awareness of health workers has always been a challenge in MWM, as highlighted by WHO in a regional workshop report on healthcare waste management [2].

Consequently, the expert's decision rated environmental public health/occupational safety practices (M6) and waste disposal (M5) as the second and third most important criteria for evaluating medical waste management in Ota, as opposed to capacity building in Myanmar [4]. This is primarily due to the significant amount of waste produced in Ota and across Nigeria. Ota records approximately 151 health facilities, excluding pharmaceutical centers, as highlighted by the Federal Ministry of Health [8]. The budget/operational cost (M2), awareness/capacity building (M7), organizational policy/management plan (M8), waste treatment (M3), waste collection and storage (M9), and waste transportation (M4) are then ranked consecutively. Table 10 shows the priorities and weights derived from the pairwise comparisons. Data are presented in the normalized column as priorities, and by dividing each entry by the column's largest value, the idealized column is generated from the normalized column. The idealized column divides the outcomes by the highest value so that the optimal selection has a priority of 1.0.

Based on the AHP analysis, H1 (largest private hospital) had the highest average ranking and best performing medical waste management practices among the selected hospitals, with a normalized value of 21.12%. H2 and H3 are ranked closely as second and third, with normalized values of 18.38% and 18.29%, respectively. Figure 5 shows the heatmap performance of all selected health centers and their corresponding criterion.

Table 10. AHP priorities/weights derived from the pairwise comparisons.

Inconsistency	IC = 0.1430	RC = 0.0986	
Criteria	**Normalized**	**Idealized**	**Ranks**
Waste Segregation, M1	0.1675	1	1
Budget/Operational Cost, M2	0.1135	0.6776	4
Waste Treatment, M3	0.0755	0.4507	7
Waste Transportation, M4	0.0693	0.4137	9
Waste Disposal, M5	0.147	0.8776	3
Environmental Public Health/Occupational Safety Practices, M6	0.1528	0.9122	2
Awareness/Capacity Building, M7	0.1122	0.6698	5
Organizational Policy/Management Plan, M8	0.0901	0.5379	6
Waste Collection and Storage, M9	0.0722	0.4310	8

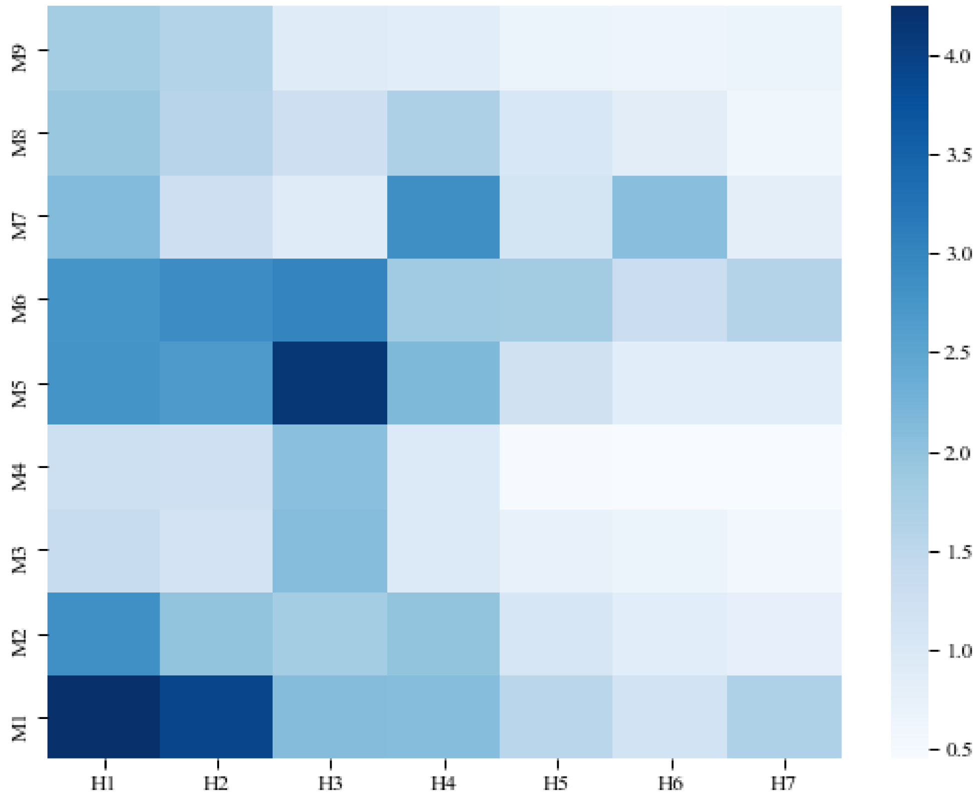

Figure 5. Analytical hierarchy process heat map showing the performance of hospitals against each criterion.

All of the public hospitals were closely ranked, with normalized values ranging from 8.05 to 9.75%. Consequently, all selected private hospitals performed better than public hospitals in the overall ranking of medical waste management assessment systems. In comparison with other health centers, waste segregation was essentially practiced in facilities H1 and H2, with the proper waste coding systems at the point of waste generation. In terms of the health workers' understanding of medical waste management and the availability of timely capacity building initiatives, H4 outperformed other health centers. Poor medical waste disposal was found in public hospitals, as they performed below par. Most medical wastes streams, such as soiled dressings, contaminated syringes, broken bottles, contaminated gloves, and blood, were found disposed by open burning, as presented in Figure 6. Most private hospitals employ the services of private sector participation (PSP) waste management agencies in collaboration with the local government to dispose of their medical wastes. It is noteworthy that these wastes are eventually mixed up with the municipal wastes stream, posing an environmental hazard to waste handlers and the general public, as scavengers and pets are seen at the disposal and dumping site.

Figure 6. Indiscriminate disposal of medical wastes.

4.2. The Results of the Fuzzy Analytical Hierarchy Process (F-AHP)

The fuzzy pairwise comparison matrix is applied to determine each criterion's weighting and the scale level for each indicator. The matrix contains elements of fuzzy comparison values $\widetilde{a_{ij}}$, dispersing the decision maker's judgement on the relative importance of element *i* over element *j*. A pairwise comparison is presented in Table 11, showing a fuzzy hierarchy on nine sets of paired comparisons. The results are described using a fuzzy linguistic scale of an equally important value of $\widetilde{1}$ to an extremely more important value of $\widetilde{9}$. The fuzzy pairwise comparison matrix is in the Supplementary Material.

Table 11. F-AHP fuzzy weights derived from the pairwise comparisons.

Criteria	Fuzzy Weights			Normalized	Idealized	Rank
Waste Segregation, M1	0.103	0.178	0.273	0.1703	1	1
Budget/Operational Cost, M2	0.067	0.114	0.186	0.1128	0.6624	5
Waste Treatment, M3	0.052	0.079	0.121	0.0773	0.4540	7
Waste Transportation, M4	0.039	0.065	0.112	0.0663	0.3896	9
Waste Disposal, M5	0.096	0.146	0.207	0.1379	0.8093	3
Environmental Public Health/Occupational Safety Practices, M6	0.078	0.135	0.253	0.1433	0.8411	2
Awareness/Capacity Building, M7	0.076	0.129	0.192	0.1219	0.7158	4
Organizational Policy/Management Plan, M8	0.053	0.084	0.164	0.0925	0.5431	6
Waste Collection and Storage, M9	0.045	0.072	0.135	0.0772	0.4533	8

AHP offers a number of advantages, such as the ease of managing several criteria to varying degrees of inconsistency. However, it cannot handle the ambiguity of preference ratings when scoring criteria—this results in the development of fuzzy AHP. Consolidating fuzzy logic with AHP solves this difficulty by providing decision makers with the possibility of expressing their opinions in terms of a range of fuzzy scale values rather than the classical AHP scale. Table 11 shows the fuzzy weights for each criterion with their normalized and idealized values.

According to fuzzy AHP, waste segregation (M1) is ranked the highest criterion, but with a higher normalized fuzzy weight of 0.1703, which is an increase of 1.67% from the assessment of AHP. As obtainable in AHP, environmental public health/occupational safety practices (M6) and waste disposal (M5) are ranked as the second and third criteria. However, awareness/capacity building (M7) with a normalized value of 0.1219 surpassed the budget/operational cost (M2) in the ranking, making it a better criterion in the assessment of medical waste management in Ota. Similarly, waste transportation (M4) is considered the lowest ranked criterion in evaluating medical waste management in Ota, as adjudicated by experts' evaluation. The priority ranking for fuzzy AHP is presented in Table 12.

Table 12. Synthesis and priorities ranking of the fuzzy AHP model.

	M1	M2	M3	M4	M5	M6	M7	M8	M9	Priorities	Rank
H1	0.0442	0.0289	0.0134	0.0120	0.0265	0.0253	0.0236	0.0195	0.0200	0.2134	1
H2	0.0379	0.0205	0.0120	0.0123	0.0245	0.0268	0.0131	0.0173	0.0167	0.1811	2
H3	0.0221	0.0174	0.0211	0.0192	0.0372	0.0299	0.0105	0.0133	0.0100	0.1805	3
H4	0.0205	0.0186	0.0101	0.0096	0.0213	0.0172	0.0314	0.0170	0.0093	0.1549	4
H5	0.0162	0.0113	0.0073	0.0047	0.0111	0.0167	0.0121	0.0108	0.0076	0.0978	5
H6	0.0144	0.0081	0.0069	0.0043	0.0090	0.0123	0.0223	0.0075	0.0077	0.0926	6
H7	0.0151	0.0081	0.0065	0.0043	0.0084	0.0152	0.0090	0.0071	0.0060	0.0796	7

Comparative to AHP, H1 is ranked the best performing hospital from the fuzzy AHP model, with a priority of 0. 2134, H2 and H3 are ranked as the second and third best performing hospitals, respectively, whereas H7 is ranked as the least performing hospital (0.0796). High priorities are seen in the criteria of waste segregation, waste disposal, and environmental public health, among highly ranked alternatives. Similarly, private hospitals performed considerably better than public hospitals. The challenge of not having an operational or running budget for waste management in public hospitals is a significant concern that limits effective medical waste management operations, as observed in criteria M2 and M8.

4.3. Comparative Validation of Results using Fuzzy TOPSIS and Sensitivity Analysis

The fuzzy technique for order performance by similarity to ideal solution (Fuzzy TOPSIS) approach is applied in order to validate the obtained results. This method is considered to be advantageous over other MCDA techniques because of its fewer or no rank reversals when alternatives are changed. In addition, it is preferable in cases of large criteria and alternatives because it avoids pairwise comparison. The stages of fuzzy TOPSIS adapted from [46] are presented below:

Step 1: Assign a rating to each of the criteria and alternatives. Assume we have a decision cluster of K members. The k*th* decision fuzzy maker's rating of alternative A*i* in relation to criterion C*j* is denoted as:

$$\widetilde{x}_{ij}^{k} = \left(a_{ij}^{k},\ b_{ij}^{k},\ c_{ij}^{k}\right) \tag{21}$$

$$\widetilde{w}_{ij}^{k} = \left(w_{j1}^{k},\ w_{j2}^{k},\ w_{j3}^{k}\right) \tag{22}$$

Step 2: Calculate the aggregated fuzzy ratings for alternatives, as well as the aggregated fuzzy weights for criteria. The aggregated fuzzy rating $\widetilde{x}_{ij}^{k} = \left(a_{ij},\ b_{ij},\ c_{ij}\right)$ of the *i*th alternative in relation to *j*th criterion is obtained as follows:

$$a_{ij} = \min_{k}\left\{a_{ij}^{k}\right\},\ b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ij}^{k},\ c_{ij}^{k} = \max_{k}\left\{c_{ij}^{k}\right\} \tag{23}$$

The aggregated fuzzy rating $\widetilde{w}_{j} = \left(w_{j1},\ w_{j2},\ w_{j3}\right)$ of the criterion C*j* is calculated by formulas:

$$w_{j1} = \min_{k}\left\{w_{j1}^{k}\right\},\ w_{j2} = \frac{1}{K}\sum_{k=1}^{K} w_{j2}^{k},\ w_{j3}^{k} = \max_{k}\left\{w_{j3}^{k}\right\} \tag{24}$$

Step 3: The normalized fuzzy decision matrix is computed. The normalized fuzzy decision matrix is $\widetilde{R} = \left[\widetilde{r}_{ij}\right]$, where

$$\widetilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^{+}}, \frac{b_{ij}}{c_j^{+}}, \frac{c_{ij}}{c_j^{+}}\right) \text{ and } c_j^{+} = \max_{i}\{c_{ij}\} \text{ (benefit criteria)} \tag{25}$$

$$\widetilde{r}_{ij} = \left(\frac{a_j^{-}}{c_{ij}}, \frac{b_j^{-}}{b_{ij}}, \frac{c_j^{-}}{a_{ij}}\right) \text{ and } c_j^{-} = \min_{i}\{a_{ij}\} \text{ (non-benefit criteria)} \tag{26}$$

or

Step 4: Calculate the weighted normalized fuzzy decision matrix. The weighted normalized fuzzy decision matrix is $\widetilde{V} = (\widetilde{v}_{ij})$, where $\widetilde{v}_{ij} = \widetilde{r}_{ij} \times w_j$

Step 5: Calculate the fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS). The FPIS and FNIS are calculated as follows:

$$A^{+} = \left(\overline{v}_1^{+},\ \overline{v}_2^{+}, \ldots,\ \overline{v}_n^{+}\right), \text{ where } \overline{v}_j^{+} = \max_{i}\{v_{ij3}\} \tag{27}$$

$$A^{-} = \left(\overline{v}_1^{-},\ \overline{v}_2^{-}, \ldots,\ \overline{v}_n^{-}\right), \text{ where } \overline{v}_j^{-} = \min_{i}\{v_{ij1}\} \tag{28}$$

Step 6: Compute the distance from each alternative to the FPIS and the FNIS. Let d_i^{+} *and* d_i^{-} be the distance from each alternative A*i* to FPIS and FNIS, respectively.

$$d_i^{+} = \sum_{j=1}^{n} d\left(\widetilde{v}_{ij}, \widetilde{v}_{ij}^{+}\right),\ d_i^{-} = \sum_{j=1}^{n} d\left(\widetilde{v}_{ij},\ \widetilde{v}_{ij}^{-}\right) \tag{29}$$

Step 7: Calculate the closeness coefficient CC_i for each alternative. For each alternative Ai, we calculate the closeness coefficient CC_i as illustrated:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{30}$$

Step 8: Finally, rank the alternatives. The best alternative is the one with the highest closeness coefficient.

A detailed calculation analysis of fuzzy TOPSIS is presented in the Supplementary Materials. The calculated weightage score in fuzzy AHP is used in obtaining the TOPSIS aggregated fuzzy rating $\widetilde{w}_j$. From the analysis, the selected nine criteria are considered beneficial against the selected alternatives, given that a positive value is considered more important. Table 13 shows the final synthesis ranking of alternatives and their closeness index using the fuzzy TOPSIS approach. Ranking priorities of alternatives corroborates with the models of AHP and fuzzy AHP. A slight rank reversal is seen among alternative H3 and H2. This demonstrates the sensitivity among its ranking criteria. For instance, H2 is ranked good in waste segregation, budget and operational cost, awareness, capacity building, and waste collection, but H3, which is ranked second, is highest in extremely rated criteria, such as waste disposal, environmental public health, and occupational safety practice. This points to the fact that a sustainable medical waste practice in a hospital must start with good waste segregation from the source point down to the sink at final disposal, where the steps involved are in accordance with sound environmental public health and occupational safety practices.

Table 13. Ranking and closeness index of alternatives using fuzzy TOPSIS.

	d_i^+	d_i^-	$d_i^- + d_i^+$	CC_i	Rank
H1	0.272531	0.937214	1.209745	0.774721	1
H2	0.512023	0.699195	1.211218	0.577266	3
H3	0.482834	0.725442	1.208276	0.600394	2
H4	0.670391	0.538376	1.208767	0.445393	4
H5	1.058571	0.152301	1.210872	0.125778	5
H6	1.094628	0.118767	1.213394	0.09788	6
H7	1.203205	0.023483	1.226688	0.019143	7

To examine the robustness of the priority ranking, a sensitivity analysis is performed. The weights assigned to the main criteria have a large significant impact on the final priorities of the alternatives. Hence, for this purpose, it can be based on occurrences that indicate different perspectives or alternative future developments on the relative importance of the criteria. The resulting changes in priorities and alternative ranking can be observed by raising or lowering the weight of specific criteria. The sensitivity analysis offers information on the stability of the ranking. A thorough evaluation of the weights is advised if the ranking is particularly sensitive to slight changes in the criteria weights. Hence, the weights of important criteria are altered separately between 0% and 100% to reflect the weights change in other criteria accordingly. The dynamic sensitivity of alternatives has been analyzed when waste segregation (M1) is increased by 30%, waste treatment (M3) is increased by 20%, waste transportation (M4) is increased by 30%, awareness/capacity building (M7) is decreased by 10%, waste disposal (M5) is increased by 25%, and environmental public health/occupational safety practices (M6) is increased by 35% from their initial levels (Figure 7).

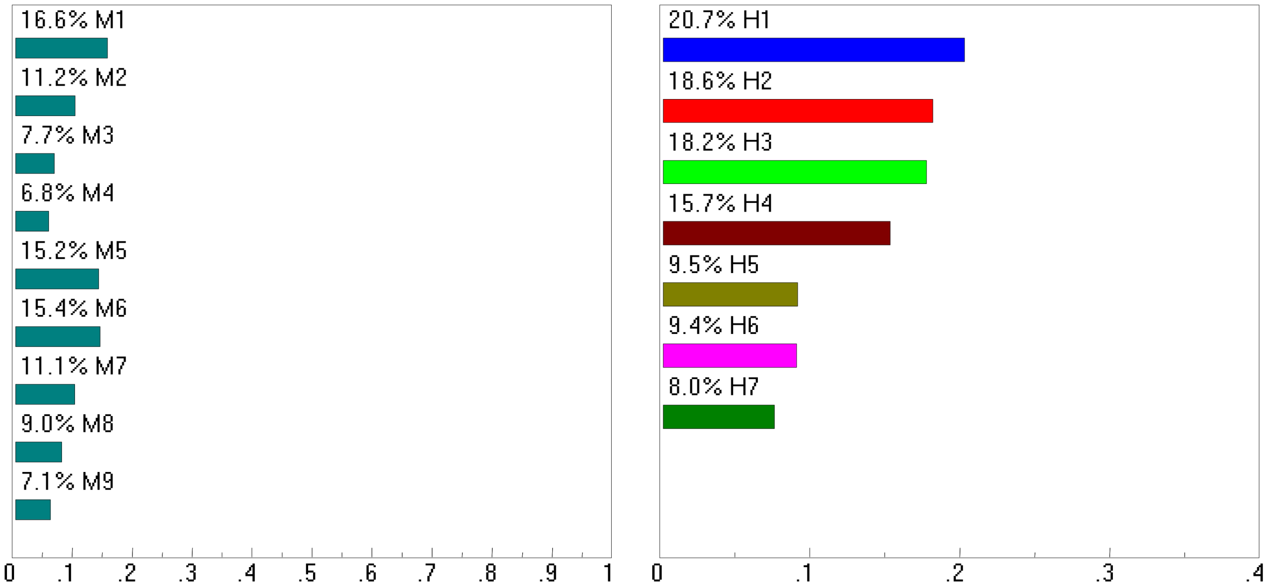

Figure 7. Dynamic sensitivity of alternatives.

Increasing waste segregation (M1) by 25% increases the global weight of "H1" from 0.207 to 0.224 (Figure 8). Increasing environmental public health/occupational safety practices (M6) by 35% takes the global weight of "H1" from 0.207 to 0.198 (Figure 9). Increasing waste disposal (M5) by 25% decreases the global weight of "H1" from 0.207 to 0.202 (check Supplementary Materials: Document S3). When waste segregation is increased, the weight of "H1" shows an upward tendency, signifying the robust standpoint of M1 practices in medical waste management for alternative "H1". Since occupational safety practices and environmental public health is generally low in selected hospitals, an increase in M6 resulted in a decrease in the weight of "H1". Hence, if health workers and waste handlers lack basic knowledge about medical waste management practices, the effectiveness is negatively impacted, increasing occupational hazards, as seen below (Figure 9). This places an urgent need for both awareness and capacity building on occupational safety practices and effective waste management operations.

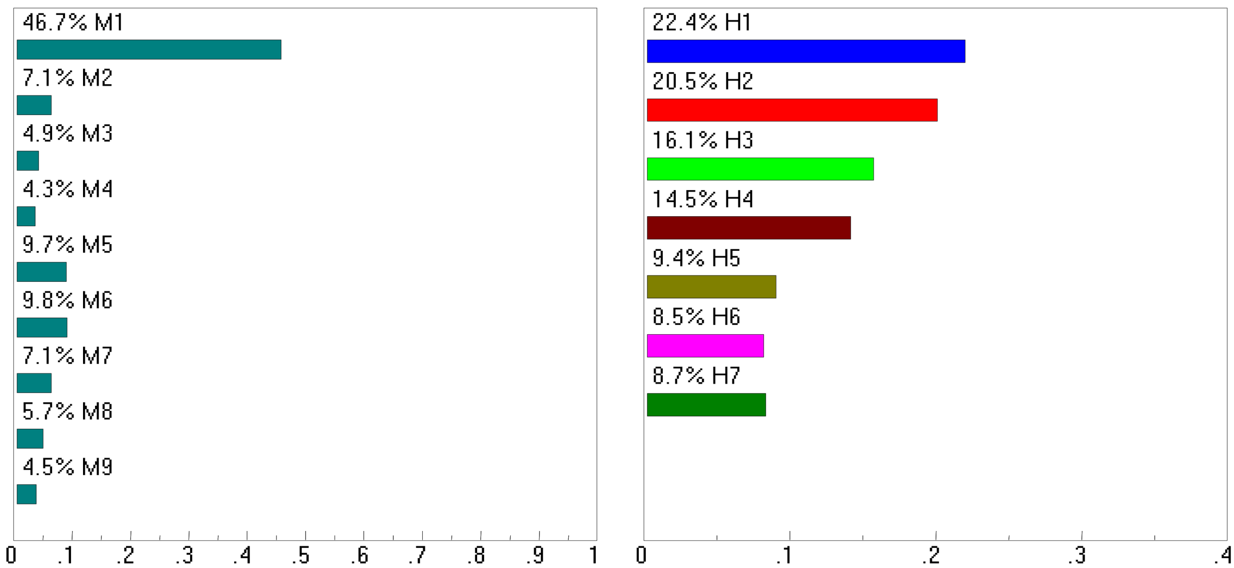

Figure 8. Dynamic sensitivity of alternatives when M1 is increased by 30%.

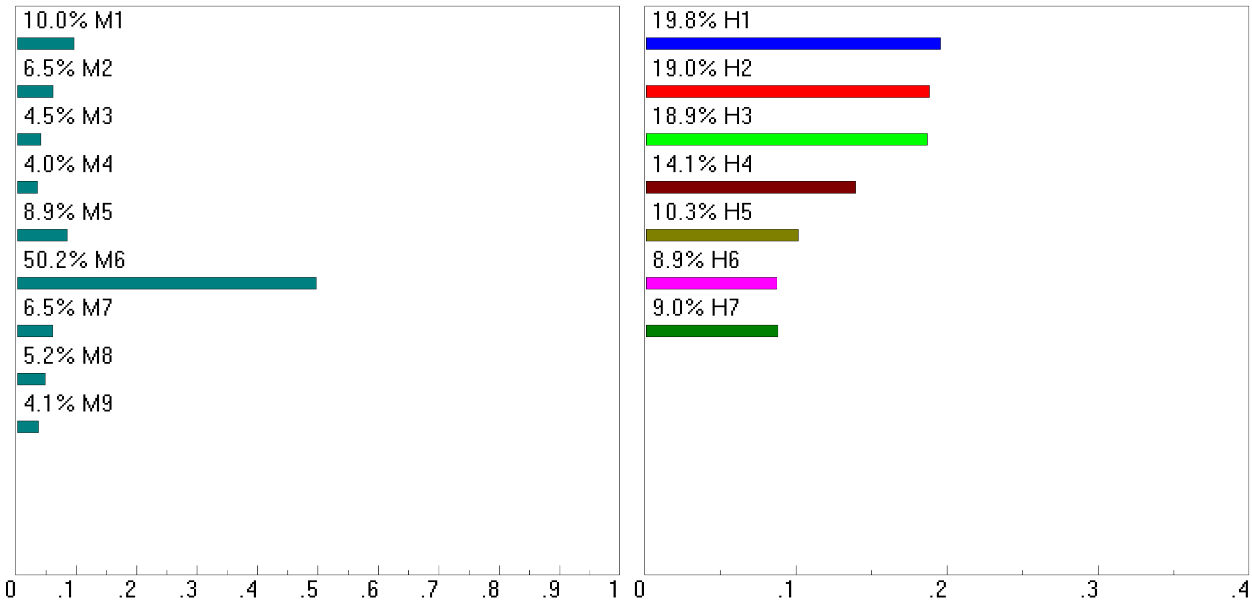

Figure 9. Dynamic sensitivity of alternatives when M6 is increased by 35%.

4.4. Implication of Medical Waste Management on Health Workers and the Public Health in Nigeria

In managing medical wastes, injuries may arise when needles, syringes, or other sharps are not collected in a secure puncture-proof container, as recommended by WHO. Consequently, the improper disposal of medical wastes poses a severe danger to health workers, waste workers, and the general public. Figure 10 shows the needle stick injuries recorded by health and waste workers in the selected hospitals. A total of 257 respondents, with 190 females and 67 males, were cross-examined. Nurses represent the largest health worker group with 41.25%, followed by medical doctors with 16.73%.

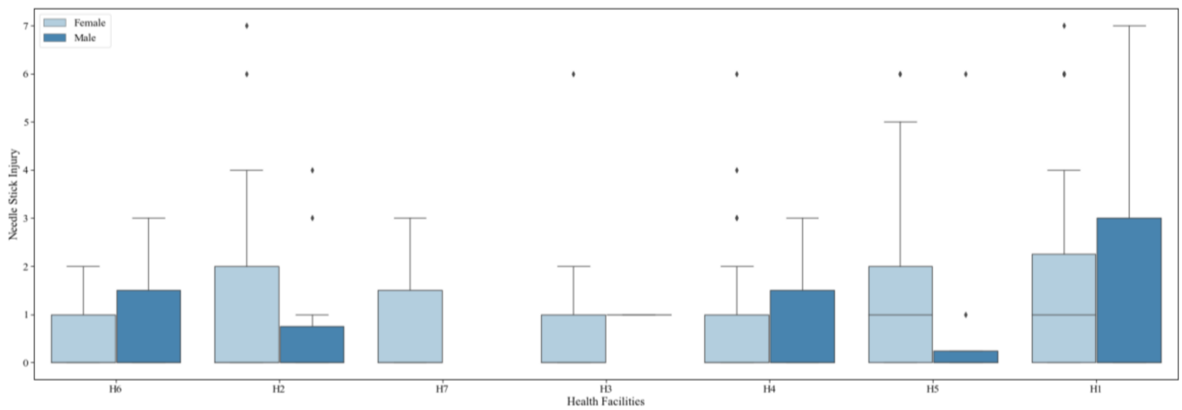

Figure 10. Needlestick injuries recorded by health and waste workers.

As highlighted in Figure 10, the highest rate of needle-stick injuries was among health personnel in the major public and private hospitals (H5 and H1, respectively), with a greater ratio (1:0.353) in females than men. Although the risk of needle-stick injuries is well known to most healthcare professionals in public hospitals, most incidents are caused by improper waste handling and disposal (Figure 6). Highly infectious wastes, such as laboratory and pathological wastes, are discarded in farmland close to the hospital. Figures 11 and 12 highlight the disposal hazard poses by medical waste to the environment and general populace. This causes serious health risks to the consumers from such farmland, as this could serve as a source for heavy metals and toxins in crops. With the advent of COVID-19, this could lead to an impediment in the disease containment.

Figure 11. Farmland containing disposal unit for pathological, laboratory, and COVID-related wastes in Ota.

Figure 12. Indiscriminate disposal of medical wastes susceptible to scavenging and pets infestation.

5. Conclusions

This research aimed to evaluate Nigeria's medical waste management systems by developing a multi-criteria decision analysis (MCDA) model to analyze selected hospitals in Ota. This was achieved by initiating two popular types of MCDA: the analytical hierarchy process (AHP) and the fuzzy analytical hierarchy process (F-AHP) models. Applying the two models with the nine WHO-based criteria, findings have shown that private hospitals better manage medical waste than public hospitals. Best hospitals thrive with key criteria, such as waste segregation. Waste segregation is a key determinant in implementing an effective waste management system in any healthcare facility. The application of the fuzzy AHP Model over the classical AHP scale is appropriate for handling the ambiguity of preference ratings during decision making. A pairwise comparison of each criterion reveals waste segregation as a key factor in managing and handling hospital wastes in any healthcare facility. In addition, findings show that waste segregation is achieved in healthcare facilities with good hospital management, organizational policies, an efficiently planned budget for waste management, and a good running operational cost. Information obtained from the questionnaires was categorized into criteria for each health facility. The inclusion of a budget/operational cost, environmental public health/occupational safety practices, and an organizational policy/management plan is novel to this research and MWM systems. In this study, the highest rate of needle-stick injuries was among health personnel in the major public and private hospitals, with a greater rate in females than men. Disposal methods investigated were mostly open burning and incessant dumping for most public health care centers. Deficient waste management practices were observed in waste transportation, waste disposal, storage and collection, and organizational policies. While the awareness and capacity building on occupational safety practices and environmental public health were well known by health workers and waste handlers, compliance and enforcement were critical challenges. Although 45.14% of health workers suffered from needle-stick injuries, there is an urgent need for awareness and capacity building on occupational safety practices and environmental public health for health workers and waste handlers. Nurses represent the largest health worker group with needle-stick injuries, followed by medical doctors. Although the risk of needle-stick injuries is well known to most healthcare professionals in public hospitals, findings reveal that most incidents are due to improper waste handling and disposal. Waste treatment is evaluated to be poor among selected health facilities. It falls below par, with reference to the WHO guidelines. The medical waste treatment and disposal in health institutions in Ota is, for the most part, inefficient and insufficient, with inadequate treatment plants and no follow-up on medical waste disposal by waste handlers. Waste collection and storage systems with appropriate color-coding systems were largely deficient in most hospitals. The adherence to the WHO-recommended segregation scheme and the National Environmental Standards and Regulations Enforcement Agency for medical waste was utterly flawed. This is mainly due to inadequate funding for waste management. This research has successfully applied the analytical hierarchy process (AHP) and fuzzy analytical hierarchy process (F-AHP) to manage wastes generated within healthcare institutions in Ota, Nigeria. To the researcher's knowledge, this is a novel study in the application of MCDA in medical waste management systems in Nigeria. This research has identified other essential benchmarks, such as: the organizational policy, management plan, environmental public health, occupational safety practices, budget planning, and operational cost as necessary criteria in the management systems of medical waste in healthcare institutions. This research has developed an assessment framework and presented both useful criteria and a synthesis of results that will guide hospital managers to effectively implement a sustainable waste management structure in their health facilities and contribute to the current research field on healthcare waste management systems. The findings from the present study can aid decision making, as this will benefit policy makers and key stakeholders in developing more comprehensive and effective medical waste management guidelines in Nigeria. A strong collaboration is required from policy makers, health workers, stakeholders, and government agencies to provide sustainable medical waste management laws and regulations in Nigeria whilst improving adequate funding for healthcare waste management. In addition, future decision-making studies could augment the results from the current research by assessing the impact of pandemic preparedness and response on medical waste management.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su131910914/s1, Table S1: AHP data analysis.xlsm, Table S2: fuzzy AHP data analysis.xlsm, Table S3: AHP normalized pairwise matrix.csv, Table S4: AHP priorities by alternative.csv, Table S5: fuzzy AHP priorities by alternative.csv, Table S6: needle-stick injury.csv, Table S7: fuzzy TOPSIS.xlsm, Document S1: Python Seaborn programming visualization syntax.docx, Document S2: AHP and fuzzy AHP flow diagram, Document S3: sensitivity analysis.

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