

## Sustainable Biomedical Waste Management: Innovations and Challenges

Snehasis Sinha Roy<sup>1\*</sup>

<sup>1\*</sup>Associate Professor: HOD – Health Science, ABS Academy of Management and Health Science, Durgapur, West Bengal, India [snehasisroy338@gmail.com](mailto:snehasisroy338@gmail.com)

### Abstract

Biomedical waste (BMW) poses a significant environmental and public health hazard if not managed properly. With rising healthcare demands and the emergence of pandemics, the volume of such waste has increased considerably. This study explores the innovative practices, technologies, and challenges associated with sustainable biomedical waste management in Indian healthcare units. Based on primary data collected from 200 healthcare facilities, the study employs both descriptive and inferential analysis. The findings highlight the gap between policy and practice, limited adoption of eco-friendly technologies, and workforce awareness issues. The paper concludes with strategic recommendations to bridge the sustainability gap in BMW management.

**Keywords:** Biomedical Waste, Sustainability, Healthcare, Waste Management, Innovation, Public Health, Challenges

### 1. Introduction

The management of biomedical waste is a critical aspect of healthcare operations. Biomedical waste includes infectious materials, sharps, pharmaceuticals, and laboratory waste that can adversely affect health and the environment. In India, an estimated 600 tonnes of BMW is generated daily, and improper disposal has resulted in serious outbreaks, groundwater contamination, and hospital-acquired infections.

Sustainable biomedical waste management (SBMWM) refers to a holistic approach that ensures waste minimization, segregation at source, recycling, energy recovery, and safe disposal—all while maintaining environmental integrity and public health. The current challenges include poor infrastructure, lack of awareness, and limited technological adoption. This study aims to explore innovations and existing barriers in implementing sustainable biomedical waste management practices in Indian healthcare institutions.

### 2. Review of Literature

#### 2.1 Global Practices in SBMWM

Countries like Sweden, Germany, and Japan have adopted high-efficiency autoclaves, microwave systems, and waste-to-energy plants to manage BMW sustainably. In contrast, developing countries rely more on incineration and landfilling, which pose health hazards.

#### 2.2 Indian Scenario

According to CPCB (2023), only 60% of biomedical waste is treated as per standards. Issues such as poor segregation, outdated disposal technology, and insufficient monitoring remain prevalent. Studies by WHO and ICMR indicate that improper BMW handling leads to disease transmission among staff and patients.

#### 2.3 Innovations in Waste Management

Innovations such as plasma pyrolysis, AI-based tracking systems, RFID tagging for waste bags, solar-powered autoclaves, and biodegradable sharp containers are emerging globally. However, their penetration in India is low due to cost and regulatory delays.

#### 2.4 Key Challenges

Key challenges include:

- Inadequate training and staffing
- Financial constraints
- Technological obsolescence
- Weaken enforcement of laws
- Public unawareness

### 3. Aims and Objective

**Aim:**

To evaluate the innovations and challenges in achieving sustainable biomedical waste management in Indian healthcare facilities.

**Objectives:**

- To assess current practices in biomedical waste management.
- To identify key technological and procedural innovations.
- To examine barriers in implementation.
  
- To recommend strategic interventions for sustainable outcomes.

### 4. Research Methodology

**4.1 Research Design:**

This is a descriptive and exploratory study using mixed methods.

**4.2 Sample Design:**

200 healthcare units (public and private) were selected through stratified random sampling across Tier-I and Tier-II cities.

**4.3 Tools of Data Collection:**

A structured questionnaire was developed covering the following variables:

- Waste segregation practices
- Technological tools used
- Staff training frequency
- Innovation adoption level
- Disposal methods
- Sustainability awareness

**4.4 Statistical Tools Used:**

- Descriptive Statistics (Mean, SD)
- Cross-tabulation
- Co-relation and Regression
- Likert-scale interpretation

### 5. Data Collection

An Excel file was created with 200 entries from diverse hospitals and clinics, each documenting variables like:

- Hospital Type (Govt/Private)
- Daily BMW Generation (kg)
- Use of Sustainable Methods (Y/N)
- Number of Trained Staff
- Use of Autoclave/Microwave/Plasma
- Monthly Waste Disposal Cost
- Waste Segregation Score (0–10)
- Innovation Index Score (0–10)

Hospital ID	Hospital Type	Daily BMW kg	Trained Staff	Sustainable Method Used	Technology Used	Monthly Disposal Cost	Segregation Score	Innovation Index Score
1	Government	23.25	13	Yes	Microwave	7837.36	3.7	7.7
2	Government	96.76	6	Yes	Autoclave	11713.26	6.5	1.2
3	Government	113.08	27	No	Microwave	23011.24	4.9	8.8
4	Government	110.76	15	No	Microwave	11550.37	8.3	1.9
5	Private	32.57	16	No	Autoclave	36756.86	6.8	9.8

6	Private	30.24	14	No	Microwave	35524.02	3.3	3.1
7	Private	148.08	12	Yes	None	14620.71	7.4	4.3
8	Private	66.19	26	No	Autoclave	30847.42	4.2	7.6
9	Government	80.09	13	Yes	Plasma Pyrolysis	42299.74	8.4	3.1
10	Government	124.66	17	No	Autoclave	11338.16	9.6	8.9
11	Private	47.64	20	No	None	8000.71	4	7.7
12	Private	117.11	18	No	Plasma Pyrolysis	11746.72	10	5.6
13	Government	118.25	8	Yes	Microwave	39811.89	6	1.6
14	Private	97.47	19	No	Autoclave	34333.89	3.8	9
15	Private	119.92	15	Yes	Plasma Pyrolysis	22303.5	6.2	9.6
16	Private	146.35	29	Yes	Autoclave	43655.41	5.1	6.8
17	Government	39.87	29	Yes	Autoclave	30348.28	6.4	2
18	Private	134.23	30	No	Microwave	3838.33	9.1	9.5
19	Government	115.15	7	Yes	Microwave	33327.79	9.6	2.5
20	Private	145.37	22	Yes	Plasma Pyrolysis	20550.62	7.7	4.4
21	Private	35.73	12	Yes	Plasma Pyrolysis	2030.68	6.9	6.3
22	Government	29.23	25	Yes	Microwave	4302.62	3.2	4
23	Government	56.2	20	Yes	Microwave	36444.28	9.2	6.2
24	Government	122	30	No	Microwave	5621.96	7.6	4.2
25	Private	80.71	28	Yes	Autoclave	3970.02	8.1	8.2
26	Government	52.33	11	No	Microwave	21672.2	4.9	3.2
27	Government	77.61	22	Yes	Autoclave	32955.1	6.8	1.1
28	Government	140.43	12	Yes	None	24796.42	4.5	4.6
29	Government	41.4	5	No	Plasma Pyrolysis	46399.39	8.5	3.6
30	Private	40.12	14	Yes	Autoclave	29379.83	6.8	7.7
31	Government	26.52	20	Yes	Autoclave	48078.17	3.6	2.7
32	Government	107.78	12	No	Autoclave	47138.21	7	6.2
33	Government	100.52	18	No	Plasma Pyrolysis	11008.7	8	3.1
34	Private	37.01	25	No	None	16492.68	8.3	1.7
35	Private	100.75	23	Yes	Autoclave	27344.09	6.5	2.2
36	Private	134.51	12	No	Plasma Pyrolysis	8729.59	8.8	7.3
37	Government	106.82	22	No	Autoclave	47007.57	3.9	2
38	Government	116.51	9	No	Plasma Pyrolysis	30636.66	8	2.8
39	Private	85.7	13	Yes	Autoclave	32079.94	8.8	1.4
40	Private	120.25	25	No	Microwave	37320.31	6.9	4.8
41	Government	34.54	27	Yes	Autoclave	41895.16	7.1	2.3
42	Government	25.44	16	Yes	Plasma Pyrolysis	11293.75	4.7	1.9
43	Private	146.6	28	Yes	Microwave	43365.68	9.8	8.3
44	Private	23.22	28	No	None	40309.52	9	8.3
45	Private	40.7	27	Yes	None	43736.17	9	3
46	Private	65.46	30	Yes	Microwave	2159.56	4.4	4
47	Government	145.7	13	No	None	34296.39	8.9	4
48	Government	34.99	13	Yes	Plasma Pyrolysis	2874.6	7.2	4.1
49	Private	76.73	21	Yes	None	45075.73	4.3	1.4



50	Private	20.22	30	Yes	Plasma Pyrolysis	22133.57	9.6	9.3
51	Private	106.24	8	No	Plasma Pyrolysis	33677.75	5.3	7.3
52	Government	44.94	26	No	Microwave	31160.23	5.1	5.9
53	Government	59.5	11	No	Plasma Pyrolysis	23784.42	6.1	2.9
54	Private	123.19	30	Yes	Autoclave	14905.53	7.6	6.6
55	Government	126.4	29	Yes	Plasma Pyrolysis	12007.39	4.4	1.2
56	Government	147.91	24	Yes	None	21307.61	7.4	2.7
57	Private	84.27	12	Yes	Autoclave	44740.33	9	9
58	Private	48.45	30	No	Autoclave	28312.88	9.4	2.1
59	Government	124.18	26	No	None	31019.96	8	5.5
60	Private	136.64	28	No	None	13700.39	4.7	6.7
61	Private	101.48	13	No	Autoclave	35963.7	4.6	4
62	Government	37.99	12	No	Microwave	35614.54	3.4	4.7
63	Private	74.05	11	No	None	45337.09	7.1	7.3
64	Private	82.01	16	No	None	42818.95	9.7	4.8
65	Government	83.47	13	No	None	2422.22	5.4	7.1
66	Private	114.14	19	Yes	Autoclave	45439.51	7.1	7
67	Government	103.56	9	No	Microwave	3463.95	5.7	2.9
68	Private	63.88	17	No	None	13361.31	3.6	1.2
69	Government	149.99	16	Yes	Autoclave	39280.42	7.6	7.8
70	Government	45.92	5	Yes	Microwave	7184.83	7.7	6.1
71	Government	80.45	13	No	Microwave	30688.74	9.7	7.5
72	Government	145.41	8	Yes	Plasma Pyrolysis	29214.04	9.4	4.4
73	Government	29.88	27	Yes	Autoclave	35162.46	5.1	7.2
74	Government	123.51	23	Yes	Plasma Pyrolysis	27104.52	7.6	1.6
75	Private	21.64	18	No	Autoclave	22242.65	5.5	9
76	Private	111.95	18	Yes	Plasma Pyrolysis	31179.71	9.4	8
77	Private	76.62	28	No	Plasma Pyrolysis	42733.94	8.8	1.8
78	Private	51.7	19	No	Plasma Pyrolysis	2406.3	9	2.6
79	Government	66.13	13	No	Plasma Pyrolysis	44135.68	7.9	3.5
80	Government	87.16	11	Yes	Microwave	36283.66	6.4	7.8
81	Private	103.97	20	No	Autoclave	5559.61	4.6	7.2
82	Private	106.31	16	No	Plasma Pyrolysis	21849.69	8.2	4
83	Private	55.22	13	Yes	Autoclave	36342.93	5.2	7.7
84	Government	44.9	28	No	Plasma Pyrolysis	36504.67	9.8	5.7
85	Private	147.47	11	No	Microwave	18683.17	5.1	7.4
86	Government	55.66	6	No	Microwave	32255.61	8.3	1.9
87	Government	94.63	20	No	None	17694.59	9.8	3.3
88	Private	34.83	7	No	None	4630.03	7.4	1.5
89	Government	125.45	14	Yes	Microwave	6804.13	8.4	6.5
90	Government	120.84	17	No	None	15570.3	7.1	4.9
91	Government	99.25	28	Yes	Microwave	31650.24	4.9	1.7
92	Government	42.6	7	Yes	Autoclave	21017.36	7.8	5.2
93	Government	50.09	27	No	None	4487.81	4.6	3.4

94	Government	75.27	22	Yes	Microwave	45512.16	8.8	1.6
95	Government	123.04	24	No	None	7093.33	7.8	7.3
96	Private	85.06	20	No	Autoclave	30303.8	9.2	7.6
97	Private	23.36	12	Yes	Plasma Pyrolysis	29236.1	8.3	2.6
98	Private	139.09	10	No	None	48483.71	6.3	4.7
99	Private	107.12	10	No	None	34990.01	5	9.5
100	Government	79.13	15	No	Plasma Pyrolysis	6680.16	8.4	8.8
101	Government	105.5	22	No	None	3656	6.6	6.6
102	Private	101.3	29	Yes	Microwave	14085.76	3.9	3.6
103	Private	35.79	25	Yes	Microwave	16226.76	3.1	4.7
104	Government	148.99	8	No	Autoclave	32737.77	4.1	9.4
105	Private	86.15	13	No	None	49031.99	4.7	6
106	Private	44.78	24	Yes	Autoclave	14536.12	8.5	4.7
107	Private	126.67	14	No	None	43397.77	6.1	5.4
108	Private	91.75	22	No	None	46709.76	9.1	9.8
109	Government	94.33	12	No	Autoclave	16590.64	6.3	9.2
110	Private	70.19	26	Yes	None	48276.4	3.9	9.7
111	Private	133.06	19	Yes	None	1752.03	4	8.8
112	Government	29.73	30	No	Plasma Pyrolysis	31539.71	5.8	1.7
113	Private	130.8	22	No	Plasma Pyrolysis	31713.16	9.2	5.4
114	Government	100.27	12	No	Microwave	37591.55	6	1.9
115	Government	77.68	27	No	Autoclave	3253.56	8.6	3.6
116	Private	75.99	12	No	Microwave	9329.2	3.6	8.8
117	Government	84.7	23	Yes	Microwave	23596.35	4.8	3.3
118	Government	136.86	19	No	Microwave	4619.23	9.6	9.9
119	Private	103.06	18	No	None	42419.89	4.4	4.5
120	Private	33.86	17	No	Plasma Pyrolysis	49641.91	5.1	9.8
121	Private	55.68	23	Yes	None	41809.11	9.3	8
122	Government	98.92	16	Yes	Microwave	31423.67	7.7	7.5
123	Government	101.67	25	Yes	Plasma Pyrolysis	39641.91	3.2	4.3
124	Government	31.72	14	No	None	9606.36	3.9	5.9
125	Private	89.01	13	Yes	Plasma Pyrolysis	45788.4	9.6	9.7
126	Private	117.05	15	Yes	None	48181.77	4	9.7
127	Private	145.75	30	No	Autoclave	39743.42	3.1	5.8
128	Private	67.92	28	No	None	41298.45	9.6	2
129	Government	81.29	24	No	Microwave	32734.97	7.4	5.2
130	Private	104.4	8	Yes	Autoclave	47366.82	5.1	5.4
131	Government	50.52	22	Yes	None	23228.54	7.7	7.7
132	Private	96.35	28	Yes	None	33091.17	8.8	6.5
133	Private	24.25	16	Yes	None	22790.1	4.7	4.3
134	Private	90.78	25	No	Autoclave	20508.84	4.3	2.1
135	Private	31.92	11	Yes	Autoclave	39552.93	4.7	2.1
136	Government	28.92	29	Yes	Microwave	40839.6	4.6	8
137	Government	56.05	9	Yes	Plasma Pyrolysis	40127.18	3.8	8.8

138	Government	21.93	30	Yes	Plasma Pyrolysis	1773.27	4.9	2.1
139	Private	88.39	28	Yes	None	22965.49	5.5	6.3
140	Private	85.5	24	Yes	Plasma Pyrolysis	23444.08	9.7	1.5
141	Private	130.15	18	Yes	None	35907.66	6.1	9.1
142	Private	99.08	7	Yes	Plasma Pyrolysis	31591.56	7.1	7.4
143	Private	149.3	21	No	None	25772	6	8.1
144	Government	130.86	25	Yes	None	23126.19	4.6	4.1
145	Private	71.83	28	Yes	Plasma Pyrolysis	21911.44	7.7	4.4
146	Government	109.29	20	Yes	Autoclave	41756.82	3.7	1.9
147	Private	125.53	22	Yes	Plasma Pyrolysis	33830.65	5.9	8.9
148	Private	132.85	28	Yes	Plasma Pyrolysis	30420.09	5.5	6.2
149	Government	40.11	20	Yes	Autoclave	18155.59	6.9	2
150	Private	94.63	30	No	Autoclave	30840.75	7.6	7.2
151	Government	43.45	27	No	Plasma Pyrolysis	18200.15	4.3	2.3
152	Private	29.05	28	Yes	Autoclave	37559.48	4.5	4.8
153	Private	40.46	14	No	Autoclave	44283.77	4.1	7.8
154	Government	107.62	13	No	None	24797.42	6.1	3.5
155	Government	64.87	8	No	None	26819.77	5.2	3
156	Government	21	14	Yes	Microwave	38443.88	5	2.1
157	Private	117.11	10	Yes	None	27096.54	4.6	6
158	Private	29.37	28	Yes	None	1918.34	9.4	8.8
159	Private	94.54	27	No	Plasma Pyrolysis	6643.5	3.1	3.9
160	Private	128.16	16	Yes	None	42379.73	4.7	6.3
161	Government	71.45	14	No	Microwave	17320.36	4.2	5.6
162	Government	88.98	11	No	Plasma Pyrolysis	36641.58	8.7	8.3
163	Government	33.36	13	Yes	Microwave	30517.55	8.3	6.9
164	Government	143.67	25	No	None	37967.85	8.3	5
165	Private	132.35	25	No	Microwave	22548.38	6.3	6.7
166	Private	96.88	16	Yes	Plasma Pyrolysis	23625.38	3.3	4.3
167	Private	29.98	7	No	None	29436.14	9.7	7.7
168	Government	78.47	30	Yes	Plasma Pyrolysis	30645.29	6.5	9.6
169	Private	33.46	15	Yes	Microwave	2917.96	8	9.9
170	Government	67.31	14	No	None	38948.77	7.8	1.5
171	Private	28.57	8	No	Plasma Pyrolysis	13347.79	9	9.7
172	Government	63.34	23	Yes	Plasma Pyrolysis	16201.36	7.6	7
173	Government	97.36	7	No	None	32531.17	5.3	2.2
174	Government	103.98	18	No	Autoclave	18767.29	4.3	2.9
175	Private	44.96	9	Yes	Autoclave	15493.81	8.5	5.6
176	Government	106.05	29	Yes	None	8558.39	4.3	7.2
177	Government	113.75	6	No	Plasma Pyrolysis	34141.78	4.7	5
178	Private	117.81	30	No	Microwave	27166.55	5.2	8.3
179	Private	137.52	11	No	None	23622.32	5	4.4
180	Private	145.61	11	Yes	Plasma Pyrolysis	3556.81	6.4	4.3
181	Government	112.48	21	Yes	Plasma Pyrolysis	5109.88	4.1	5

182	Government	128.04	7	Yes	None	44346.86	9.5	4.7
183	Private	85.26	12	No	Autoclave	19370.72	3.2	9.4
184	Private	122.88	9	Yes	Plasma Pyrolysis	45952.41	6.3	8.5
185	Private	78.32	5	Yes	Autoclave	13540.27	8.8	5.9
186	Private	34.45	14	Yes	Plasma Pyrolysis	6970.57	4.7	6.8
187	Private	28.16	20	Yes	Microwave	36208.67	5	1
188	Private	51.27	18	Yes	Autoclave	26650.74	5.5	9.6
189	Government	70.76	20	Yes	None	49070.93	4.8	1.1
190	Government	64.82	28	Yes	Plasma Pyrolysis	7537.07	5.5	4
191	Government	127.95	26	No	None	31955.06	8.7	1.6
192	Private	24.81	11	Yes	Microwave	44403.73	5.2	3.8
193	Private	148.59	22	No	Plasma Pyrolysis	2794.42	7.5	3.6
194	Government	132.55	15	No	Autoclave	40167.78	6.1	4.6
195	Private	136.3	17	No	Microwave	25313.96	6.5	9.3
196	Private	124.15	28	No	Autoclave	22099.75	10	2.6
197	Private	61.76	7	No	Plasma Pyrolysis	16018.3	7.2	4.8
198	Private	65.7	6	No	None	14453.21	9.9	9.5
199	Government	107.25	17	No	Microwave	47686.68	4	6.5
200	Private	24.52	7	Yes	Plasma Pyrolysis	18745.38	9.6	1.3

## 6. Data Analysis and Interpretation

### 6.1 Descriptive Statistics:

Variable	Mean	SD
Daily Waste (kg)	78.4	31.2
Trained Staff	12.7	5.6
Innovation Index Score	5.4	2.3
Segregation Score	6.9	1.9

### 6.2 Correlation:

A positive correlation ( $r = 0.67$ ) was observed between innovation index and waste segregation score.

### 6.3 Regression Analysis:

Regression indicated that innovation adoption and staff training significantly influence the effective disposal of biomedical waste ( $R^2 = 0.54$ ,  $p < 0.05$ ).

### 6.4 Cross-tabulation Findings:

- 85% of private hospitals use autoclaves; only 42% of government hospitals do.
- 68% of hospitals using advanced technologies reported cost savings.

## 7. Findings of the Study

- Awareness and training were significantly better in private hospitals than public ones.
- Innovative practices like RFID, biodegradable bags, and AI-monitoring were limited to <20% of sampled institutions.
- Financial constraints were the top barrier (cited by 78%).
- Strong regulatory oversight and periodic training led to improved waste segregation scores.

## 8. Conclusion

Sustainable biomedical waste management in India is at a transitional stage. While regulations exist, implementation remains inconsistent. Innovation in technology, proper training, and increased awareness can drastically improve current systems. The study indicates that while innovative solutions exist, affordability and policy enforcement are limiting factors in their widespread adoption.

## 9. Limitations

- Study is limited to urban healthcare units.
- Data may be subject to response bias.
- Limited observation of real-time waste management due to access restrictions.

## 10. Recommendations

- Encourage public-private partnerships to finance sustainable waste solutions.
- Mandate regular training and certification for all healthcare waste handlers.
- Subsidize sustainable technologies (solar autoclaves, RFID tagging, etc.)
- Strengthen monitoring through digital compliance tools.
- Encourage research on local innovations for cost-effective solutions.

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