

Statistical Spatial Modeling of Agricultural Waste Using Geographic Information Systems (GIS): A Case Study of the Nile Delta

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Abstract

Agricultural waste remains a critical environmental and developmental challenge in Egypt, particularly in the Nile Delta, where intensive farming generates large amounts of crop residues that often lead to air pollution, soil degradation, and greenhouse gas emissions. Effective management of this waste requires spatially informed approaches that link environmental data with policy decisions.

This study suggest a geospatial statistical framework aligns with the Central Framework for a System of Population and Social Statistics (CF-SPSS), integrating multi-source data (administrative records, labour force surveys, and geospatial satellite imagery). GIS operationalizes the Places pillar. integrating remote sensing and Geographic Information Systems (GIS) to improve identification, collection, and valorization of agricultural residues.

The framework distinguishes two levels of action: At the state level (national/central): The framework enables authorities to map residue hotspots, quantify available biomass, and identify priority zones for collection, recycling infrastructure, and bioenergy investment. This supports macro-level planning and policymaking, and at the village/community level (local): The same framework empowers farmers, youth, and agricultural cooperatives to utilize freely available satellite products for their own local planning. They can identify nearby residue concentrations, organize small-scale collection and baling, and establish micro-projects such as composting, mushroom cultivation, or biogas units – transforming waste into local economic opportunities. With the rapid advancement of artificial intelligence systems, along with the increasing availability of free, ready-to-use satellite imagery, the ability to employ such geospatial tools by non-specialist individuals (farmers, youth, cooperative members) becomes merely a matter of time.

By bridging the state and local levels, this framework transforms “rice residues” from a silent statistical figure into active “resource flows,” enabling national policy and local action to work together. The framework is replicable across other agricultural residues and regions, supporting SDG 12 (Responsible Consumption and Production) and SDG 11 (Sustainable Cities and Communities).

Keywords: agriculture, geographic information system, sustainable-development, waste management, Geospatial Analysis, CF-SPSS Framework, Circular Economy

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1. Introduction:

Historically, the concept of agricultural “waste” was absent; traditional farming lifestyles absorbed all byproducts into local cycles as livestock feed, soil fertilizers, and household fuel. However, the rise of the capitalist economy and the prioritization of cash crops turned these residues into environmental burdens. Intensive farming generates large amounts of crop residue, most notably rice straw—which have historically led to severe air pollution, soil degradation, and greenhouse gas emissions. Among these, the annual “Black Cloud” phenomenon stands out as one of Egypt’s most critical environmental crises, blanketing Cairo and the Nile Delta with thick smoke and directly affecting public health.

As early as 2006, Author master’s thesis laid the groundwork for a spatial approach to this [1] problem. That research developed a work plan based on selecting rice cultivation concentration zones located in the prevailing wind pathways that carried emissions toward Cairo, specifically targeting areas overlapping with high-density residential communities. It was early recognition that effective intervention required not only agricultural data but also an understanding of atmospheric transport and population exposure.

Today, the conceptual framework has evolved. Agricultural residues—such as rice straw, cotton stalks, corn stalks, wheat and bean straws, vegetable tops, tree pruning remains, and canal cleaning by products are no longer viewed solely as waste to be managed but rather economic resources.

Based on reports from the Ministry of Environment and the Waste Management Regulatory Authority (WMRA), Egypt generates between 30 and 35 million tons of agricultural residues annually, equivalent to 40–50% of the primary crop yield. Recycling agricultural residues, particularly rice straw, generated over 1.2 billion EGP (over USD 25 million) in economic return within one year [2], showcasing a major shift in transforming waste into value-added products like fodder, compost, and wood. The management of these residues in the Nile Delta now represents a multidimensional challenge that bridges environmental sustainability and national economic growth. The transition from traditional disposal methods to a **circular bio-economy** is no longer optional; it is a statistical and developmental necessity [3].

A circular economy is an economy that is restorative and regenerative by design, and which aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles [3] it breaks the concept down into three core principles:

- Preserve and enhance natural capital: By controlling finite stocks and balancing renewable resource flows.
- Optimize resource yields: By circulating products, components, and materials at the highest utility at all times in both technical and biological cycles (this means prioritizing repair and reuse over recycling).
- Foster system effectiveness: By revealing and designing out negative externalities (such as pollution, carbon emissions, and land use).

The plan does not rely on random estimates; rather, it adopts a **centralized statistical system** built upon two internationally recognized pillars: the **Central Framework for a System of Population and Social Statistics (CF-SPSS)**[4] and a dedicated **spatial statistics framework** aligned with United Nations standards (such as the Global Statistical Geospatial Framework). This dual framework integrates (cultivated areas monitored by satellites) and (logistical locations calculated by GIS), transforming “rice residues” from a silent statistical figure into active “resource flows” that support the circular economy.

Crucially, this framework redefines rice straw not as a secondary environmental problem to be solved, but as a **primary industrial feedstock within a circular bio-economy**. By utilizing spatial optimization, we ensure that biological nutrients and technical materials are kept within the production cycle, maximizing resource productivity and minimizing systemic leakage.

By embedding this geospatial-statistical approach into national policy, the research ensures that developmental decisions are evidence-based, spatially aware, and socially inclusive. It aligns Egypt’s local agricultural policies with international standards, directly contributing to Sustainable Development Goals **SDG 12 (Responsible Consumption and Production)** and **SDG 11 (Sustainable Cities and Communities)**. The findings also build upon and significantly extend the spatial insights first developed in the 2006 master’s thesis—moving from identifying vulnerable populations to designing a comprehensive, resource-oriented circular economy strategy.

2. Objective

This research aims to develop a strategic framework for the sustainable management of agricultural residues in Egypt, shifting the paradigm from conventional waste disposal to a circular bio economy. The framework integrates Remote Sensing (RS) and Geographic Information Systems (GIS) with the Central Framework for a System of Population and Social Statistics (CF SPSS).

3. METHODOLOGY

3.1. Data Sources

The methodology distinguishes between two levels of administrative data to ensure accuracy:

- **Annual Data:** Agricultural residue statistics are obtained from the **Ministry of Agriculture and Land Reclamation (MALR)** and its affiliated directorates. These datasets are issued **annually at the Governorate level**.
- **District-Level Data (Markaz):** Highly granular data at the **Markaz level** is sourced from the **National Agricultural Census**, which is typically conducted every **ten years**. This provides the necessary baseline for spatial distribution analysis.

3.2. Spatial Coverage and Priority Ranking

The study covers the major rice-producing governorates in the Nile Delta, prioritized according to their total cultivated area and production volume as follows:

1. Dakahlia
2. Sharkia
3. Kafr El-Sheikh
4. Beheira
5. Gharbia
6. Damietta
7. Port Said
8. Kalyoubia

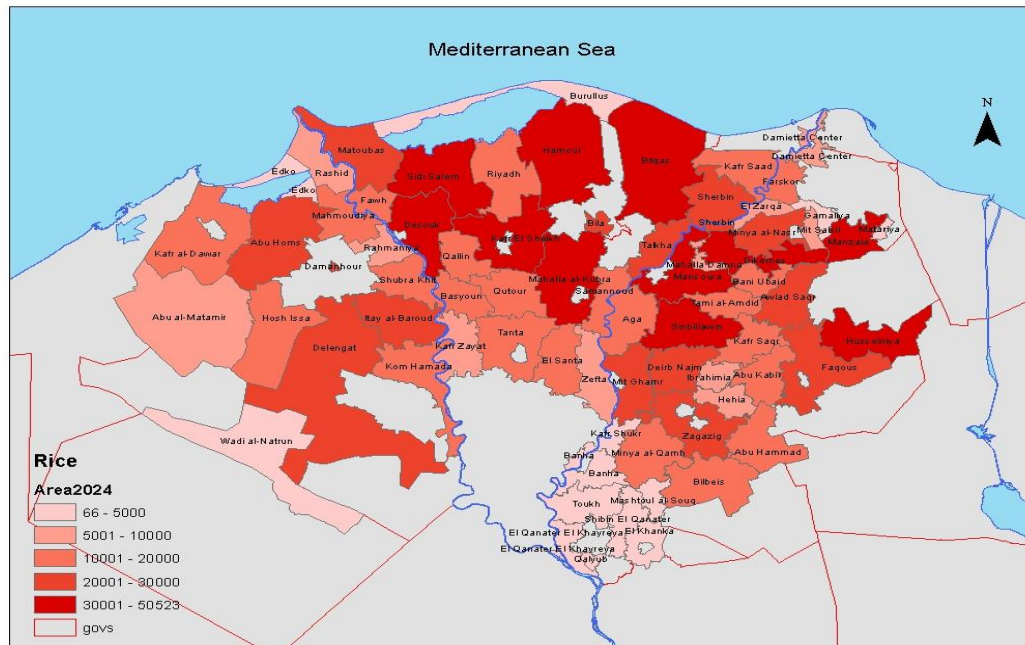
3.3. Rice Straw as a Proxy

Rice straw is utilized as the primary representative model for all agricultural residues in this study. This selection is based on two critical factors:

- **Intensive Cropping and Time Constraints:** Due to the **intensive farming system** in the Delta, farmers face a very narrow time window to clear their fields after the rice harvest to prepare for the subsequent winter crop. This urgency often compels farmers to dispose of residues quickly—historically through open-field burning—to avoid planting delays.
- **Logistical and Storage Challenges:** Rice straw poses a significant logistical burden due to its low bulk density and large volume. **Baling (compression)** is identified as the strategic solution to this challenge. If the baling and collection system can effectively manage the high volume and time-pressure of rice straw, the model can be seamlessly generalized and applied to other agricultural residues that are typically easier to handle and store.

Map 1 (to be inserted): Rice cultivated area in the Nile Delta (2024). The leading (Markaz) are Husseiniya, Bilqas, Sinbillawin, Hamoul, Mansoura, Kafr El Sheikh, Manzala, Sidi Salem, and Dikernes.

Map (1): Rice Cultivated Area in the Nile Delta (2024)



3.4 Remote sensing data and indices

Several previous review papers exist on the use of remote sensing for agriculture, highlighting the diverse range of satellite platforms currently in use. A significant advantage in the modern era is the free availability of high-quality satellite imagery [5].

Sentinel-2 (A+B) Level-2A imagery (10 m resolution) was obtained from the Copernicus Data Space Ecosystem. The following indices and composites were used:

NDVI (Normalized Difference Vegetation Index): The primary tool for identifying healthy crops and their growth stages). It leverages the fact that healthy vegetation reflects high amounts of Near-Infrared (NIR) light while absorbing red light for photosynthesis.

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

where NIR = Band 8, Red = Band 4. NDVI identifies photosynthetic activity and growth stages.

False color composite (NIR-Red-Green):

Red channel ← NIR (Band 8), Green channel ← Red (Band 4), Blue channel ← Green (Band 3).

- Flooding stage: dark blue/black (water absorbs NIR).
- Peak growth: intense red (strong NIR reflectance).
- Harvest stage: pink/tan/golden-brown (chlorophyll decline).

SWIR composite (SWIR1-NIR-Green): sensitive to moisture content, useful for distinguishing rice from other crops.

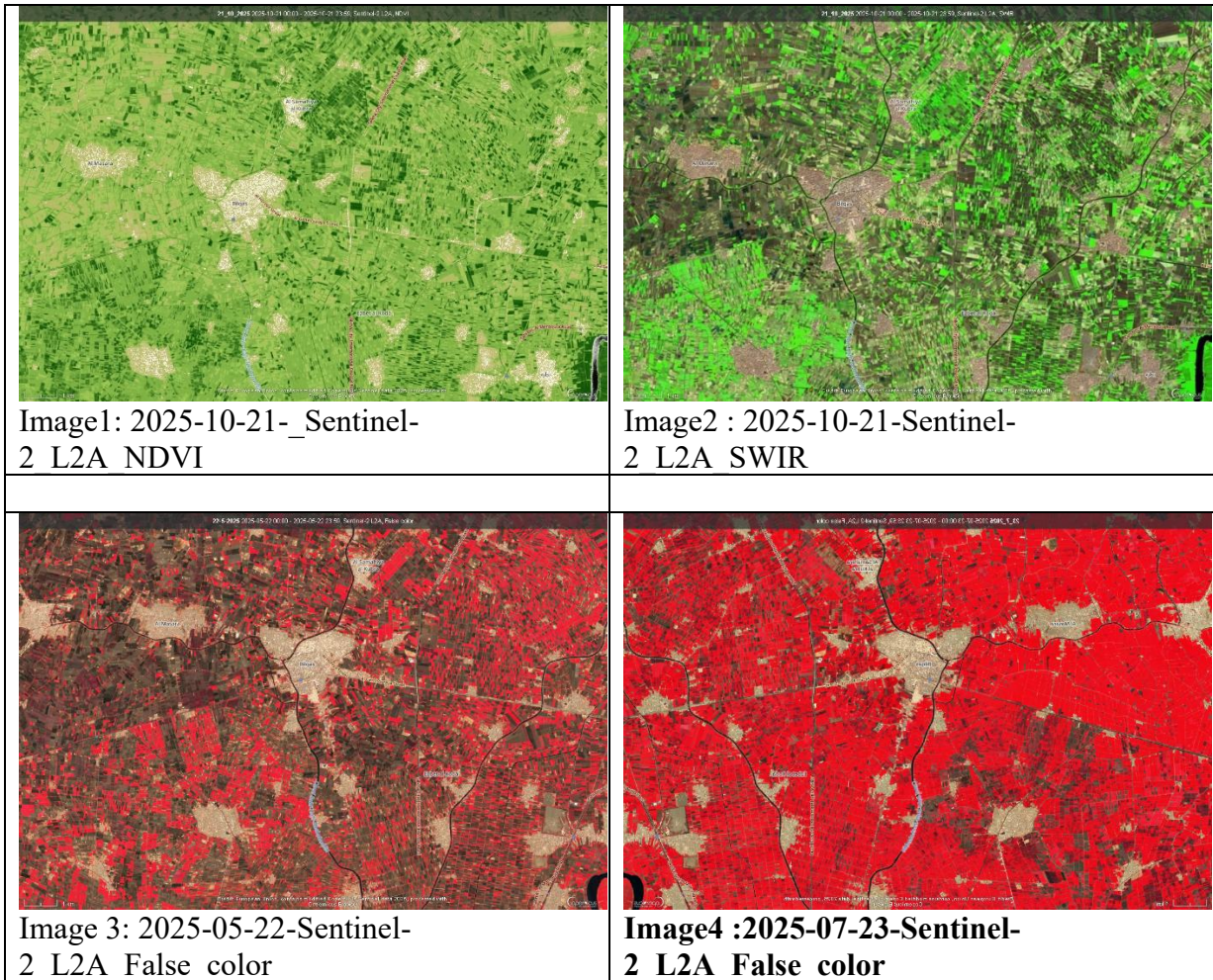
Images 1–4 for Bilqas, Dakahlia,:

Image 1: NDVI, October 2025 (late stage).

Image 2: SWIR composite, same date.

Image 3: False color composite, May 2025 (flooding stage). Fields appear **dark blue or black**.

Image 4: False color composite, July 2025 (peak growth) As the rice canopy covers the water, the color shifts to a **vibrant**.



Source : European Space Agency (ESA). (2024). Sentinel-2 MSI Level-2A imagery. Retrieved from Copernicus Data Space Ecosystem. <https://dataspace.copernicus.eu/> .

3.5 Quantification of rice straw and *its utilization*:

In Egypt, rice production averages 1.25 tons of straw per ton of rice [2]. For 2024, projected straw production is 3.9 tons per feddan, equivalent to approximately 4.8 tons of straw per feddan of rice. These coefficients allow GIS to estimate available biomass per Markaz.

3.5.1 Rice straw utilization

3. various methods to manage and repurpose agricultural waste, specifically rice straw, to align with economic and social development goals. Here is a categorized summary:

1. Agricultural & Livestock Applications

- **Organic Fertilizer (Compost):** Producing aerobic compost to cover fertilizer needs for Egyptian lands.
- **Alternative Fodder:** Using treated rice straw (via ammonia or urea) as a substitute for traditional hay and growing "green fodder" on straw beds to bridge the feed gap in summer.

- **Soilless Farming:** Using straw bales as a cultivation medium to avoid soil-borne diseases, reduce pesticide use, and provide root insulation.

2. Industrial & Energy Uses

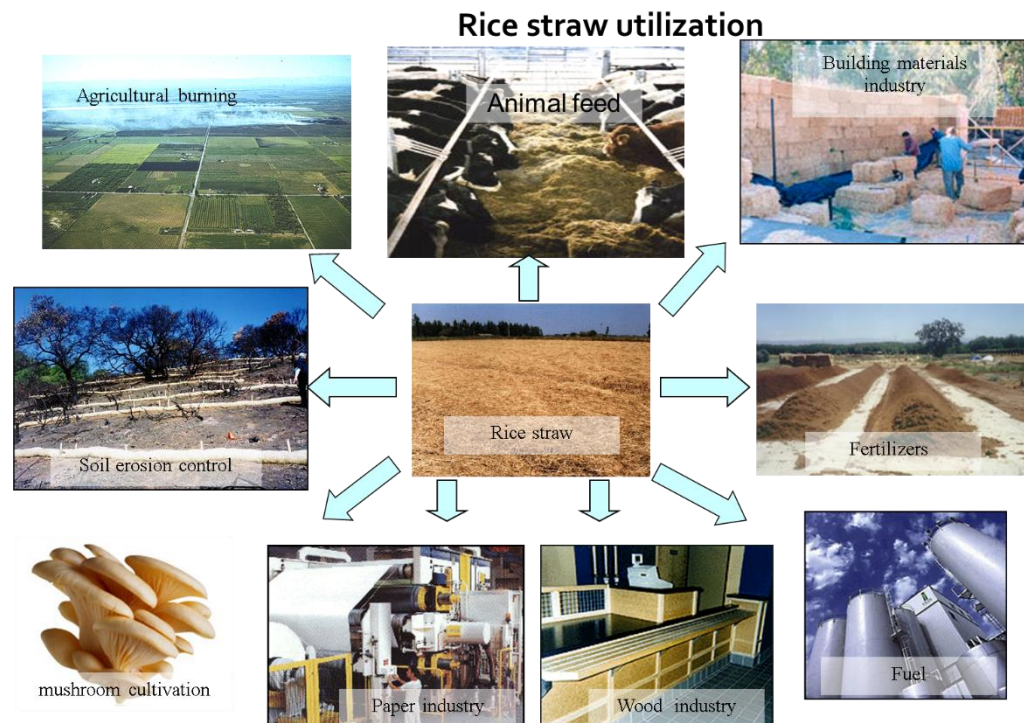
- **Paper & Cardboard:** Utilizing straw as a primary source for pulp to reduce imports, while emphasizing the need to solve the "Black Liquor" waste problem.
- **Mushroom Production:** Encouraging small and large-scale farming of Oyster and European mushrooms for local consumption and export.
- **Biogas Production:** Generating renewable energy through anaerobic fermentation, especially for remote areas.

3. Construction & Environmental Protection

- **Eco-Friendly Building:** Constructing low-cost, quick-build houses, mosques, and farms using straw bales (popular in the USA and Australia).
- **Erosion Control:** Using straw cylinders/rolls to combat soil erosion, desertification, and flash floods.

4. Logistics & Management

- **Baling & Transport:** Emphasizing the importance of mechanical baling to reduce size and transportation costs, suggesting a redistribution of machinery based on harvest timing and farm size.



3.6 Data integration and the CF-SPSS framework

All datasets were harmonized to a common geodatabase (UTM 36N projection) and aggregated to Markaz level. The framework follows the Central Framework for a System of Population and Social Statistics (CF-SPSS), which links statistical and geospatial data through five pillars. Geographic Information Systems (GIS) act as the integrating engine, transforming abstract social data into actionable spatial intelligence as follows:

- **People** (Demographic mapping): GIS pins demographic data to specific coordinates, enabling hotspot analysis of farming communities. This identifies exact locations of vulnerable groups (e.g., elderly farmers or female-headed households) to target services precisely. For rice straw management, this means locating households that need baling support or are most exposed to burning emissions.
- **Relationships** (Social network geography): GIS maps the physical reach of agricultural cooperatives, baler owners, and collection hubs. This reveals gaps in service coverage and helps design efficient village-level collection routes.
- **Outcomes** (Horizontal integration): GIS overlays disparate data layers – for example, correlating satellite-derived smoke dispersion with local health clinic records of respiratory illness. This provides direct evidence of the health benefits of reducing open burning.
- **Places** (Geostatistical precision): A national geostatistical grid (e.g., 1km × 1km cells) standardizes social and agricultural data into fixed spatial units. This ensures that even the most remote rural pockets are visible in the data, operationalizing the pledge to leave ‘No One Behind’. For this study, the grid allows estimation of straw biomass per cell, not just per Markaz.
- **Time** (Spatiotemporal evolution): GIS enables longitudinal analysis by stacking historical maps (e.g., land use from 2006, 2016, 2024) against current Sentinel-2 imagery. This visualizes trends such as the expansion of rice cultivation, the persistence of burning hotspots, and the long-term impact of waste-to-value projects. Table (1) shows data sources for agricultural waste.

Based on the 2024 labor force surveys conducted by the **Central Agency for Public Mobilization and Statistics (CAPMAS)** [6], In 2024, unemployment rates in rice-growing governorates: Beheira 6.5%, Sharqia 4.6%, Gharbia 8.4%, Dakahlia 3.4%, Kafr El-Sheikh 3.2%. These data inform social impact assessments of waste-to-value projects. (CAPMAS,2025)¹see Table (3).

Table (1) data source:

Data Category	Sources	Purpose
Remote Sensing	Sentinel-2 (10 m resolution), Landsat-8/9, annual crop classification maps *Free sources)	Delineate rice cultivation areas, monitor crop rotation, estimate straw yield potential
Administrative boundaries	National mapping authority (Egypt Survey Authority), CAPMAS	Define <i>Markaz</i> boundaries; enable spatial aggregation
Population & social data	CAPMAS census (2017), household surveys (Labour Force Survey LFS)[6]	Locate vulnerable residential clusters; assess exposure (linked to 2006 findings)
Infrastructure	Ministry of Transportation, WMRA, field surveys, CAPMAS	Road networks, existing waste collection points, potential processing sites
Environmental	Prevailing wind direction data (Egyptian Meteorological Authority), air quality stations (EEAA), and CAPMAS	Model transport of emissions; identify high-impact zones (continuation of 2006 wind-path analysis)
Agricultural statistics	Ministry of Agriculture, WMRA, CAPMAS	Straw production coefficients per feddan, seasonal calendars

4. RESULTS

4.1 Spatiotemporal increase in agricultural waste

Between 2019 and 2023, agricultural waste in the Nile Delta increased by an estimated 18%.

4.2 Hotspot identification

Hotspots of rice straw generation are concentrated in Kafr El-Sheikh, Dakahlia, and Beheira. Table (2) presents cropped and rice-cultivated areas by governorate alongside unemployment rates.

Table2: Total of Cropped Area According to Governorates & Estimation of Labour force (15 years & above) Unemployed rate 2023/2024

Governorate	Unemployed rate%			Cropped Area: Feddan	Rice cropped area by Feddan
	Male	Female	Total		
Total	4.2	17.1	6.6	12418324	1271594
Cairo	9.2	21.0	11.9	364.0	0.0
Alexandria	5.1	19.1	8.1	82705.0	1496.0
Port Said	7.8	40.3	18.1	125238.0	33580.0
Suez	9.8	29.1	14.7	22024.0	353.0
Damietta	3.3	17.3	6.1	167990.0	44309.0
Dakahlia	2.4	8.4	3.4	1131895.0	362421.0
Sharkia	3.9	8.5	4.6	1320485.0	249264.0
Kalyoubia	4.7	22.4	8.6	239634.0	10135.0
Kafr-El- sheik	2.1	7.1	3.2	940513.0	248954.0
Gharbia	5.8	16.1	8.4	637419.0	116597.0
Menoufia	2.7	10.7	4.9	455869.0	86.0
Behira	4.3	17.6	6.5	1221349.0	186662.0
Ismaelia	5.3	23.5	9.3	219163.0	8790.0
Giza	4.9	23.4	7.6	147217.0	0.0
Beni- Suef	2.7	15.5	6.1	523300.0	866.0
Fayoum	2.8	7.9	3.4	656847.1	8081.0
Menia	2.2	15.5	5.0	865691.0	0.0
Asyout	2.5	19.9	4.4	592778.0	0.0
Suhag	2.2	13.2	2.9	619286.0	0.0
Qena	1.0	13.9	1.8	321447.0	0.0
Aswan	2.4	41.0	8.4	534025.0	0.0
Luxor	2.3	21.6	4.5	158996.0	0.0
Red Sea	11.4	38.1	16.7	2180.0	0.0
El-wadi El-Gidid	4.7	15.5	6.9	708071.0	0.0
Matrouh	3.8	19.1	4.8	97412.0	0.0
North Sinai	-	-	-	1956.0	0.0
South Sinai	14	16.7	14.6	3006.0	0.0

Unemployment Rate = No. Unemployed / Labour Force * 100

Source: CAPMAS, 2024.

4.3. The Role of GIS in Turning Data into Action

Linking these figures with Geographic Information Systems (GIS):

1. Identifying Hotspots: Instead of random searching, GIS identifies areas with high productivity density, making it easier to direct balers and equipment to them.
2. Optimizing Routes: It helps map the shortest routes for transporting straw from fields to collection centers (cloud sites), reducing fuel costs and carbon emissions

3. Plant Location: It helps investors identify the best locations for establishing factories (paper, compressed wood, or organic fertilizer) based on proximity to raw materials.
 4. Economically: Converting 4.8 tons/acre of waste into raw material increases farmers' income and creates jobs in the transportation and recycling sector.
 5. Environmentally: Instead of burning these quantities and releasing carbon dioxide, the carbon is captured in useful products or converted into compost, restoring nutrients to the soil.
4. Data Integration (Remote Sensing + GIS).

5. DISCUSSION

5.1 Comparison with the 2006 baseline study

The 2006 master's thesis [1] identified vulnerable populations downwind of burning sites using wind direction and residential density. The current study extends that work by providing an operational, spatially explicit logistics model that not only identifies risk zones but also prescribes collection routes, baling locations, and facility siting. The increase from 95,641 tons of total reported waste in 2019 to 127,287 tons in 2022 (Table 1) reflects both real growth in rice cultivation and improved monitoring.

5.2 Alignment with international frameworks

The adoption of the UN Global Statistical Geospatial Framework (GSGF) moves the approach beyond ad-hoc mapping. By linking people (farmers, labour force), places (Markaz boundaries, fields), and time (seasonal harvest windows), the framework supports dynamic decision-making. This is consistent with SDG 12 (Responsible Consumption and Production) and SDG 11 (Sustainable Cities and Communities).

5.3 Comparison with other rice-producing regions

Two dominant schools of agricultural waste management exist:

- Labour-intensive/local sustainability (China, India): Relies on small-scale biogas (over 8 million units in China) and mushroom cultivation (86.8% of global oyster mushroom production).
- Capital-intensive/industrial solutions (California, USA): Focuses on large-scale paper and timber manufacturing,

The researcher suggests a hybrid model that incorporates international experiences. In areas characterized by **small landholdings** and limited infrastructure, the Ministry of Agriculture and The extension sector, which can be defined as the network of services, programs, and institutions that facilitate the flow of agricultural knowledge and technologies to farmers and rural communities, serving as an intermediary between the sources of agricultural knowledge production and its users, 10–50% of agricultural products are discarded annually as waste.

The framework leverages the transition from expert-dependent remote sensing to **Open-Source Geospatial Intelligence**. By utilizing free, ready-made Sentinel-2 products, the technical and financial barriers to entry are removed, enabling local stakeholders to transform 'silent statistical figures' into active 'resource flows' without the need for specialized deep-analysis software.

6. Conclusion:

Our research proves that agricultural waste in the Nile Delta is not an environmental burden, but a strategic socioeconomic asset. By implementing an 'Integrated Statistical and Socio-Economic Framework,' we move from 'Estimated Guesses' to 'Data-Driven Accountability.' This approach transforms 35 million tons of residues into the engine of a 'Circular Economy,' ensuring that waste management is no longer a cost center, but a profitable and sustainable resource system.

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