Demographic Dynamics and Household and Similar Waste Generation in Urban and Peri-Urban Areas: The Case of El Hadjar, Berrahal, and Ain Berda Districts of Annaba Province, North-East Algeria

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Abstract. This study investigates the relationship between population growth and household and similar waste (HSW) production in three inland districts of Annaba Province (Algeria): El Hadjar, Berrahal, and Ain Berda. We hypothesize that population growth in these districts is positively correlated with increases in HSW production, and that waste composition reflects both local consumption patterns and the activity of an informal recovery sector operating upstream of formal collection systems. A methodological approach combining demographic projections, waste flow quantification (2022–2023), and morphological characterization using the MODECOM method was applied. Demographic projections indicate significant population increases across all three districts by 2030, with growth rates ranging from approximately 7% (Ain Berda) to 14% (El Hadjar). HSW production, estimated between 0.68 and 0.99 kg/inhabitant/day, increased by 6.12% overall between 2022 and 2023. A Pearson correlation analysis reveals a near-perfect positive linear relationship between commune-level population size and annual HSW tonnage ($r = 0.9998$, $p < 0.001$), confirming the central hypothesis. Morphological analysis highlights a dominant proportion of organic matter (57%), followed by complex compounds (21%) and plastics (15%), consistent with consumption patterns typical of cities in the Global South. Marked seasonal production peaks coincide with the Ramadan period (March–April) and the summer influx (July–August). The low proportion of dry recyclable materials is consistent with the documented presence of an informal recovery sector. These findings underscore the need for integrated, territory-specific waste management strategies that incorporate demographic projections and recovery infrastructure adapted to the predominantly organic waste profile.

Keywords: household and similar waste (HSW), demographic dynamics, population growth, urbanization, waste characterization, MODECOM method, informal recovery sector, Annaba, Algeria.

1. Introduction

The management of household and similar waste (HSW) represents a major environmental, health, and socio-economic challenge on a global scale. Rapid population growth, accelerated urbanization, and changing consumption patterns have all contributed to a significant increase in the volumes of waste generated. According to World Bank estimates, annual waste production currently estimated at nearly 2 billion tonnes could reach 3.4 billion tonnes by 2050 (Kaza & Van Woerden, 2018).

The consequences of inefficient waste management are manifold. The uncontrolled accumulation of waste leads to soil and groundwater pollution, compromises the quality of aquatic ecosystems (particularly marine ecosystems) and contributes to the deterioration of air quality, especially in cases of uncontrolled combustion. These impacts directly affect public health, particularly in densely populated urban areas.

To limit these effects, a number of strategies are being implemented worldwide. These include reducing waste at source, recycling materials, composting organic waste, recovering energy through incineration, and using controlled landfill sites for non-recyclable residues. However, it is difficult to generalize these practices in developing countries, where infrastructure is often inadequate and management policies remain insufficiently effective (Mertenat & Zurbrügg, 2024). Lack of investment, low public awareness, and the absence of a binding regulatory framework are all obstacles to be overcome. In this context, the transition to a circular economy has emerged as a strategic alternative, based on reducing waste at source and maximizing its recovery (Ntsonde, 2022).

Algeria faces structural challenges in HSW management. Rapid urban growth, driven by rural-to-urban migration and the concentration of populations in metropolitan areas, places considerable pressure on basic infrastructure such as housing, sanitation, transport, and public health. Governance is also often hampered by a lack of institutional coordination, chronic underfunding, and poor availability of reliable data to guide public policy (Hachemi-Douici & Dorbane-Nasri, 2022).

The wilaya (province) of Annaba, in north-east Algeria, illustrates these issues clearly. Population growth expected in the coming decades will exacerbate the pressures already exerted on waste collection and treatment systems. According to national projections, Algeria's population will reach 55 million inhabitants by 2025, with an increasing share concentrated in large metropolitan zones (Atik et al., 2020).

The three inland districts of Annaba (El Hadjar, Ain Berda, and Berrahal) display distinct characteristics in terms of HSW production and management. These areas, often distant from major urban centres, face several constraints: inadequate collection facilities, a lack of sorting centres, scarce recovery channels, and insufficient mechanisms for monitoring and evaluating waste flows.

A range of studies on waste generation in university and urban contexts in the Global South has highlighted the central role of demographic and socio-cultural factors in shaping waste composition and

production rates (Hoornweg & Bhada-Tata, 2012; Kaza et al., 2018). Research conducted in comparable contexts notably in Morocco (Aboulaiche & Gallad, 2023), other Algerian cities (Attalah & Meftah, 2024; Bensmail & Bouzadi, 2021; Cheniti et al., 2020), and Sub-Saharan African municipalities (Zhu et al., 2008); consistently identifies population growth, urbanization, and informal recovery as key determinants of waste dynamics. However, few studies explicitly quantify the statistical relationship between population growth and HSW production at the district level in Algeria, particularly in territories characterized by mixed urban-peri-urban gradients.

The aim of this study is therefore to (i) quantify and characterize HSW in the three inland districts of Annaba Province over the period 2022–2023, (ii) project population trajectories through 2030 using demographic modelling, and (iii) statistically assess the relationship between population size and HSW production at the commune level. The study also aims to interpret the morphological composition of waste in relation to local consumption patterns and the role of the informal recovery sector.

Research hypothesis: Population growth in the inland districts of Annaba Province is positively correlated with increases in HSW production, and the dominant organic fraction of the waste reflects local dietary patterns while the low proportion of dry recyclables indicates significant upstream diversion by informal waste recovery actors.

Population growth expected in these three districts is likely to worsen the situation if corrective action is not taken promptly. Anticipating this growth and improving local waste management systems are therefore essential steps toward sustainable management, in line with national and international sustainable development objectives (Hassaine & Abrika, 2023; UNEP, 2023).

2. Materials and methods

2.1. Geographical and demographic context of the wilaya of Annaba

The wilaya of Annaba, located in north-eastern Algeria (Fig. 1a), lies approximately 700 km from Algiers. It is bounded by the Mediterranean Sea to the north, the Wilaya of El Tarf to the east, the Wilaya of Skikda to the west, and the Wilaya of Guelma to the south. It covers an area of 1,439 km², with a recorded population of 793,172 in 2019 (MICL, 2021). The wilaya has an 80 km coastline and is administratively divided into six districts, three coastal (Annaba, El Bouni, and Chétaibi) and three inland: El Hadjar, Berrahal, and Ain Berda (Fig. 1b).

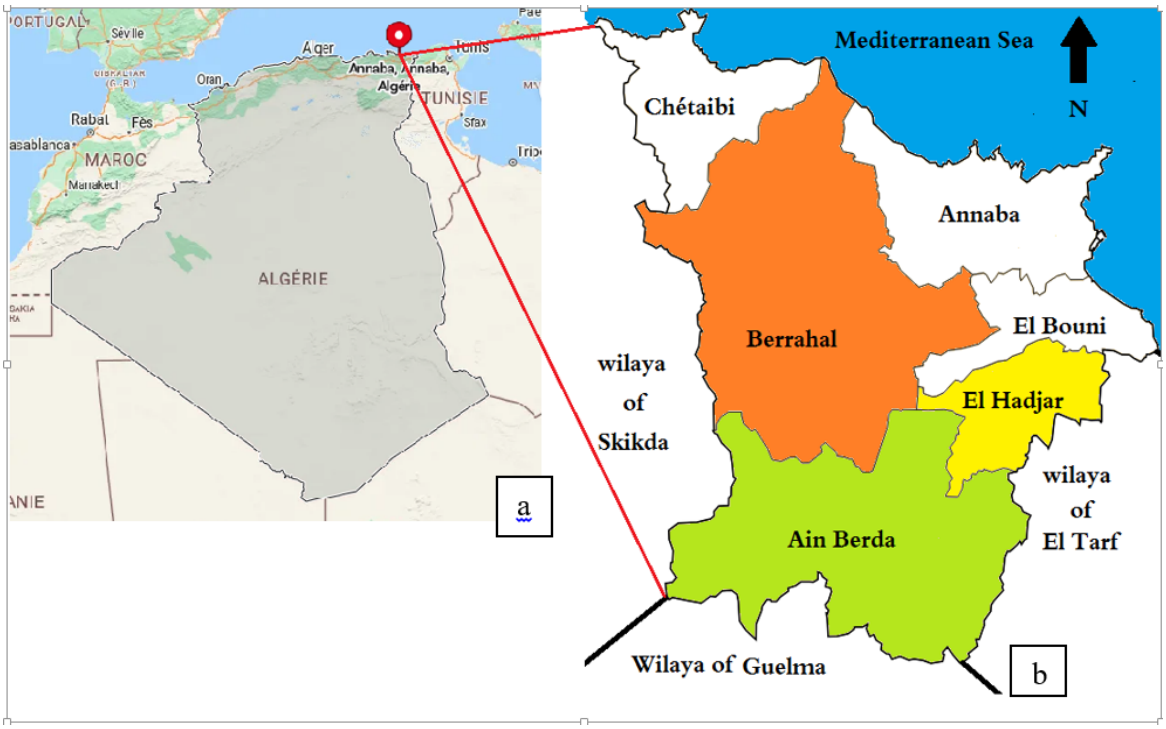

Figure 1. Geographical location of the Wilaya of Annaba (a) and its six districts (b).

2.2. Household and similar waste quantification

To characterize HSW composition in 2022, a stratified random sampling procedure was applied: 36 waste containers were selected across the three districts (three containers per month over twelve months), ensuring representation of different urban morphologies, population densities, and seasonal periods. The containers were distributed proportionally to the population of each commune and were selected from distinct residential, commercial, and institutional land-use zones. A total of 1,440 kg of waste was manually sorted from these containers. The MODECOM™ 2017 method, recommended by the French Environment and Energy Management Agency (ADEME, 2021), was used to classify waste into six categories: organic matter, plastics, paper and cardboard, glass, metals, and complex compounds, with contextual adaptations to local waste types.

The choice of 36 containers was determined by balancing statistical representativeness and operational constraints. This sample size is consistent with MODECOM guidelines for medium-sized municipalities (ADEME, 2021) and allowed the collection of a minimum of 1,440 kg of waste , a quantity sufficient for reliable compositional analysis (Hoornweg & Bhada-Tata, 2012). The urban population of the three districts was estimated at 259,326 inhabitants as of 2022, based on demographic projections from the 2008 general population census (RGPH, 2008).

2.2.1. Calculation of the HSW generation ratio and population estimation

The HSW generation ratio (R) (defined as the quantity of waste generated per inhabitant per day) is a standard indicator used to compare waste production across regions and to identify trends over time. It is calculated using the formula:

$$R = Q / (P \times T)$$

Where: R = ratio (kg/inhabitant/day); Q = total waste quantity over the period (kg); T = duration of the period (365 days); P = total population concerned.

Population size was estimated using the geometric progression formula:

$$Pt = P_0 \times (1 + r)^{(t-t_0)}$$

Where r is the annual growth rate for each commune as recorded by the RGPH (2008). The values presented in Tables 1–3 were estimated using this formula, with base populations and growth rates derived from the 2008 census. For example, for the commune of El Hadjar (r = 1.0% per year): $P_{2022} = 37{,}364 \times (1 + 0.01)^{14} = 42{,}949$ inhabitants.

2.2.2. Statistical analysis: correlation between population and HSW production

To quantitatively assess the relationship between population size and HSW production across communes, a Pearson correlation coefficient (r) was calculated for both 2022 and 2023 datasets, using commune-level annual waste tonnage and estimated commune population as paired variables (n = 8 communes). The coefficient of determination (R^2) was derived to quantify the proportion of variance in HSW production explained by population size. A linear regression model (HSW = a × Population + b) was also fitted to enable forward projection of waste volumes in relation to projected population growth. Statistical significance was set at $p < 0.05$.

3. Results

Waste production is closely linked to population growth. Higher population density and improved living standards together drive increased waste volumes, creating public health challenges, environmental pollution, and elevated economic costs. Urban expansion, industrial development, and shifting consumption patterns further amplify this trend.

3.1. Demographic situation in the districts of El Hadjar, Berrahal, and Ain Berda

3.1.1. The district of El Hadjar

The district of El Hadjar has experienced continuous and regular population growth over the projection period 2020–2030. Starting from a baseline of 37,364 inhabitants recorded in the 2008 census (RGPH, 2008), the district population reached 140,472 inhabitants in 2020 and is projected to reach 159,550 by 2030. The municipality of Sidi Amar, one of the most densely populated in the wilaya of Annaba, will see its population rise from 98,370 in 2020 to 113,042 in 2030 — representing a projected growth of

approximately 14.9% over the decade. The municipality of El Hadjar itself is expected to reach 46,508 inhabitants in 2030 (Table 1).

Table 1. Population projections for the district of El Hadjar, 2020–2030

Year	El Hadjar	Sidi Amar	District El Hadjar
2020	42,103	98,370	140,472
2021	42,524	99,747	142,270
2022	42,949	101,143	144,092
2023	43,378	102,559	145,938
2024	43,812	103,995	147,807
2025	44,250	105,451	149,701
2026	44,693	106,927	151,620
2027	45,140	108,424	153,564
2028	45,591	109,942	155,533
2029	46,047	111,481	157,528
2030	46,508	113,042	159,550

3.1.2. The district of Berrahal

The district of Berrahal presents peri-urban and rural characteristics, with a lower population density than the coastal districts. In 2008, it had a population of 49,795 inhabitants (RGPH, 2008), rising to 62,973 by 2020. This growth is projected to continue, reaching an estimated 69,446 inhabitants in 2025 and 76,585 in 2030 — a decennial increase of approximately 21.6%. The commune of Berrahal is expected to grow from 28,702 inhabitants in 2020 to 34,987 in 2030. Similarly, the population of Oued Aneb is projected to reach 32,602 in 2030, while the municipality of Tréat is projected to grow from 7,526 in 2020 to 8,996 in 2030 at an annual growth rate of approximately 1.8% (Table 2).

Table 2. Population projections for the district of Berrahal, 2020–2030

Year	Berrahal	Oued Aneb	Tréat	District Berrahal
2020	28,702	26,745	7,526	62,973
2021	29,276	27,280	7,662	64,217
2022	29,861	27,825	7,800	65,486
2023	30,458	28,382	7,940	66,780
2024	31,068	28,949	8,083	68,100
2025	31,689	29,528	8,229	69,446

2026	32,323	30,119	8,377	70,818
2027	32,969	30,721	8,528	72,218
2028	33,628	31,336	8,681	73,645
2029	34,301	31,962	8,837	75,101
2030	34,987	32,602	8,996	76,585

3.1.3. The district of Ain Berda

Classified as the second-largest district by surface area after Berrahal, Ain Berda forms part of the peri-urban zone and is mainly characterized by farmland and pastures, resulting in relatively low population density. The commune of Ain Berda is the most densely populated in the district, with 25,232 inhabitants in 2020, projected to reach 29,865 in 2030. The municipality of Eulma is also experiencing significant demographic growth, with its population expected to rise from 12,629 in 2020 to 14,948 in 2030. By contrast, the smaller Cheurfa commune shows more moderate growth, from 10,484 inhabitants in 2020 to 11,020 in 2030, reflecting an annual growth rate of approximately 0.5% (Table 3). The overall district population is projected to increase from 48,345 in 2020 to 55,833 in 2030, representing growth of approximately 15.5%.

Table 3. Population projections for the district of Ain Berda, 2020–2030

Year	Ain Berda	Eulma	Cheurfa	District Ain Berda
2020	25,232	12,629	10,484	48,345
2021	25,661	12,844	10,536	49,041
2022	26,097	13,062	10,589	49,748
2023	26,541	13,284	10,642	50,467
2024	26,992	13,510	10,695	51,197
2025	27,451	13,739	10,749	51,939
2026	27,917	13,973	10,803	52,693
2027	28,392	14,211	10,857	53,459
2028	28,875	14,452	10,911	54,238
2029	29,366	14,698	10,965	55,029
2030	29,865	14,948	11,020	55,833

3.1.4. Overall demographic dynamics of the three inland districts

The three districts of El Hadjar, Berrahal, and Ain Berda share a general trend of steady population growth between 2020 and 2030, while exhibiting distinct growth intensities that reflect their respective

geographical and economic characteristics. The district of El Hadjar, driven by industrial activity (notably steel production), shows the most pronounced growth, followed by Berrahal — whose proximity to the urban center of Annaba sustains migration-driven expansion — and Ain Berda, where agricultural land use limits demographic densification (Fig. 2). Together, the three districts are projected to grow from 251,790 inhabitants in 2020 to 291,968 inhabitants in 2030, an increase of approximately 16%.

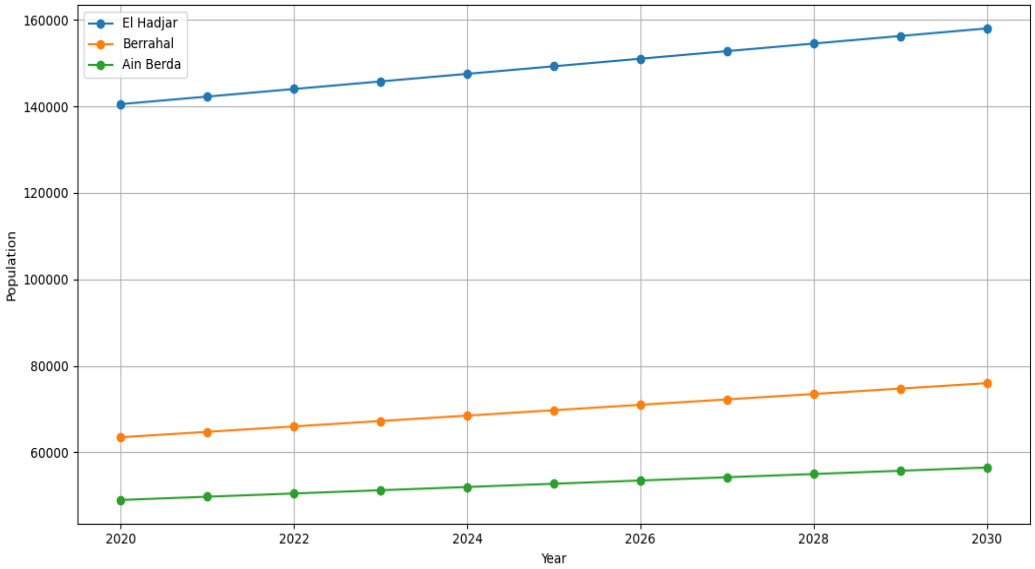

Figure 2. Projected population trends in the three inland districts of Annaba over the period 2020–2030.

3.2. Household and similar waste collection in the inland districts of Annaba (2022–2023)

3.2.1. The district of El Hadjar

3.2.1.1. Monthly tonnages in the municipality of El Hadjar

HSW collection in the municipality of El Hadjar increased from 11,831 tonnes in 2022 to 12,274 tonnes in 2023, corresponding to generation ratios of 0.75 and 0.78 kg/inhabitant/day, respectively. The highest monthly collection was recorded in April 2022 (1,185 tonnes) and March 2023 (1,116 tonnes), coinciding with the Ramadan period. Conversely, the lowest tonnages were recorded in February, with 862 tonnes in 2022 and 874 tonnes in 2023 (Fig. 3).

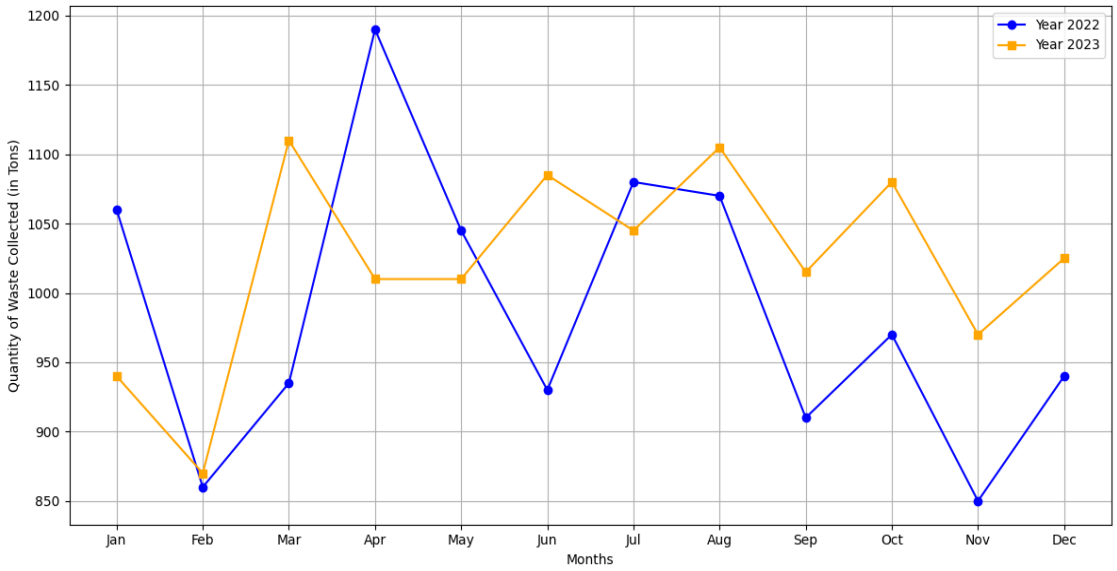

Figure 3. Monthly HSW collection in the municipality of El Hadjar in 2022 and 2023.

3.2.1.2. Monthly tonnages in the municipality of Sidi Amar

HSW collection in Sidi Amar increased by approximately 2.8%, from 28,435 tonnes in 2022 to 29,221 tonnes in 2023, with generation ratios of 0.77 and 0.78 kg/inhabitant/day, respectively. The busiest months, on average, were March and April, exceeding 90 tonnes per day. In 2023, a notable decrease was observed in November (1,758 tonnes), while in 2022 the lowest volume was recorded in December (2,097 tonnes) (Fig. 4).

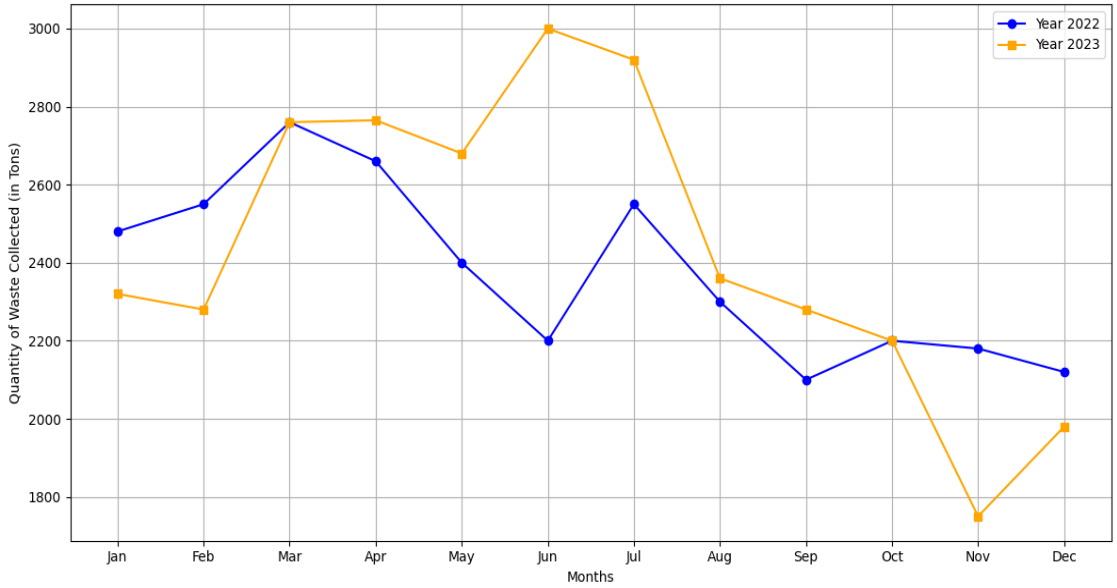

Figure 4. Monthly HSW collection in the municipality of Sidi Amar in 2022 and 2023.

3.2.2. The district of Berrahal

3.2.2.1. Monthly tonnages in the municipality of Berrahal

Annual HSW collection in the municipality of Berrahal rose from 9,598 tonnes in 2022 to 10,067 tonnes in 2023, marking an increase of 4.9%. The generation ratio thus increased from 0.88 to 0.91 kg/inhabitant/day. The largest monthly volumes were recorded in March and April 2023 (997 and 915 tonnes, respectively), while the lowest value was observed in February (699 tonnes). In 2022, a summer peak of 1,081 tonnes was recorded in July, while November recorded the lowest quantity at 699 tonnes (Fig. 5).

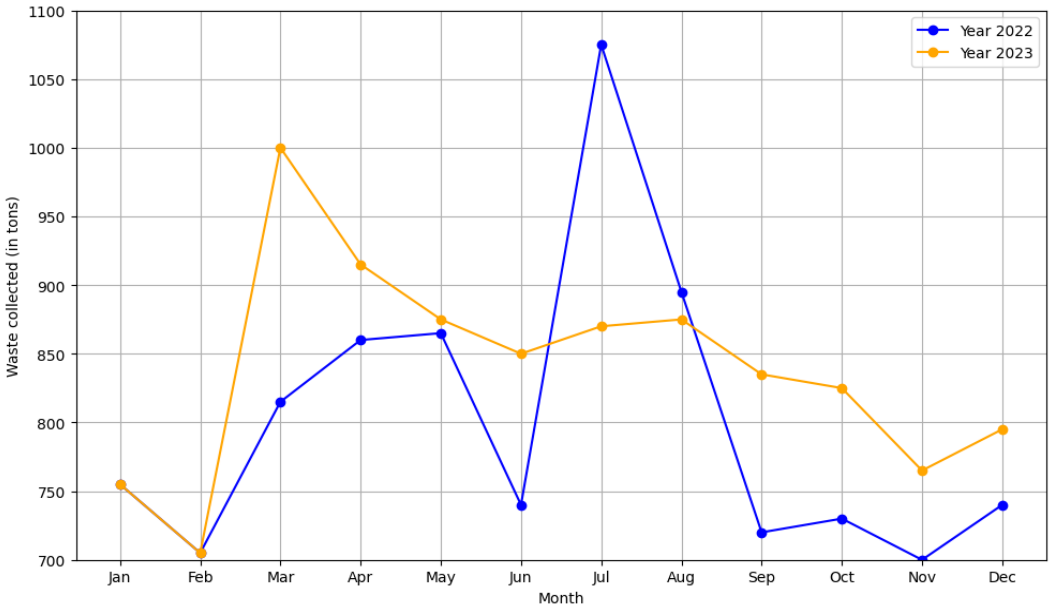

Figure 5. Monthly HSW collection in the municipality of Berrahal in 2022 and 2023.

3.2.2.2. Monthly tonnages in the municipality of Oued Aneb

Oued Aneb recorded the most pronounced HSW increase of all communes studied, with an increase of 27.6% between 2022 and 2023. Total collection rose from 8,024 tonnes in 2022 to 10,239 tonnes in 2023, with generation ratios of 0.79 and 0.99 kg/inhabitant/day, respectively. April 2022 saw a peak of 965 tonnes, while in 2023 collection exceeded 1,000 tonnes. This exceptional increase may reflect an expansion of formal collection coverage within the commune, rather than solely population growth, and warrants further monitoring (Fig. 6).

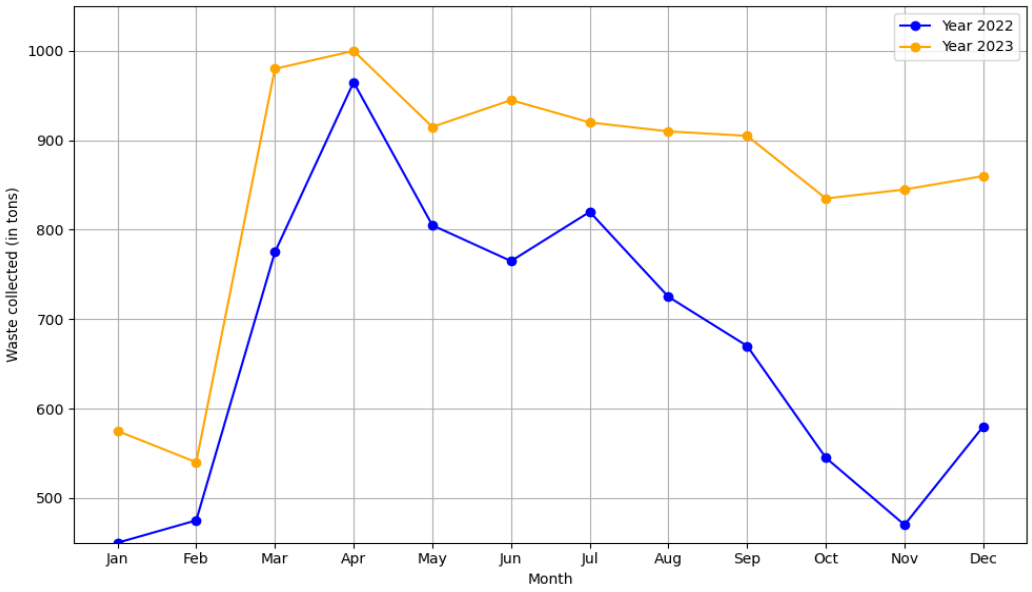

Figure 6. Monthly HSW collection in the municipality of Oued Aneb in 2022 and 2023.

3.2.2.3. Monthly tonnages in the municipality of Tréat

HSW collection in Tréat increased modestly by 2.9%, from 2,039 tonnes in 2022 to 2,098 tonnes in 2023. In 2022, the highest volumes were recorded in April and June (194 and 230 tonnes, respectively). In 2023, elevated volumes were recorded in June, August, and September. The HSW generation ratio remained stable at an average of 0.72 kg/inhabitant/day over both years, reflecting the relatively stable socio-demographic conditions of this commune (Fig. 7).

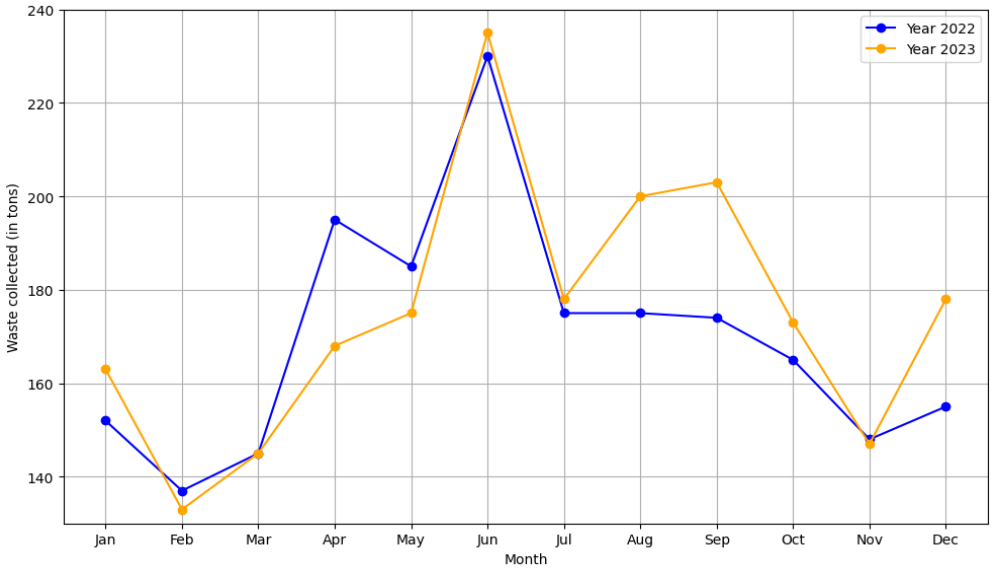

Figure 7. Monthly HSW collection in the municipality of Tréat in 2022 and 2023.

3.2.3. The district of Ain Berda

3.2.3.1. Monthly tonnages in the municipality of Ain Berda

HSW collection in the municipality of Ain Berda increased by 2.9%, from 7,130 tonnes in 2022 to 7,338 tonnes in 2023 (+208 tonnes). Monthly variations remained modest, with notable increases in January (591 to 626 tonnes), March (600 to 623 tonnes), and December (541 to 604 tonnes). July and August recorded the highest volumes in both years, exceeding 630 tonnes, consistent with the summer influx pattern. The generation ratio increased marginally from 0.75 to 0.76 kg/inhabitant/day between 2022 and 2023 (Fig. 8).

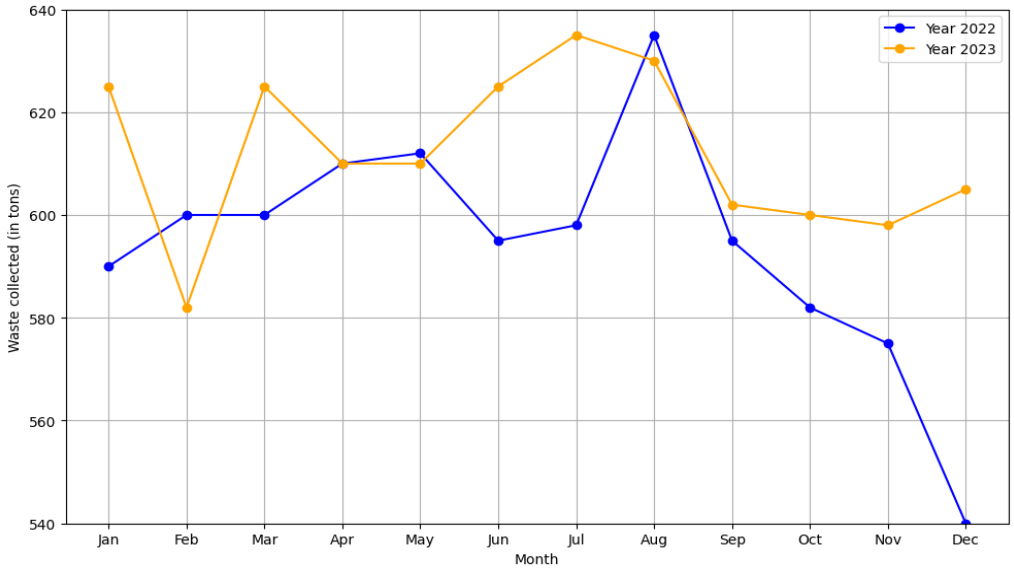

Figure 8. Monthly HSW collection in the municipality of Ain Berda in 2022 and 2023.

3.2.3.2. Monthly tonnages in the municipality of Cheurfa

HSW collection in Cheurfa increased by 5.05%, from 2,634 tonnes in 2022 to 2,767 tonnes in 2023 (+133 tonnes). The peak collection in 2023 was recorded in March (297 tonnes), while the lowest quantity was recorded in October (202 tonnes). In 2022, the peak was in May (287 tonnes), with the lowest in September (197 tonnes). The generation ratio rose from 0.68 to 0.71 kg/inhabitant/day, the lowest among all communes studied (Fig. 9).

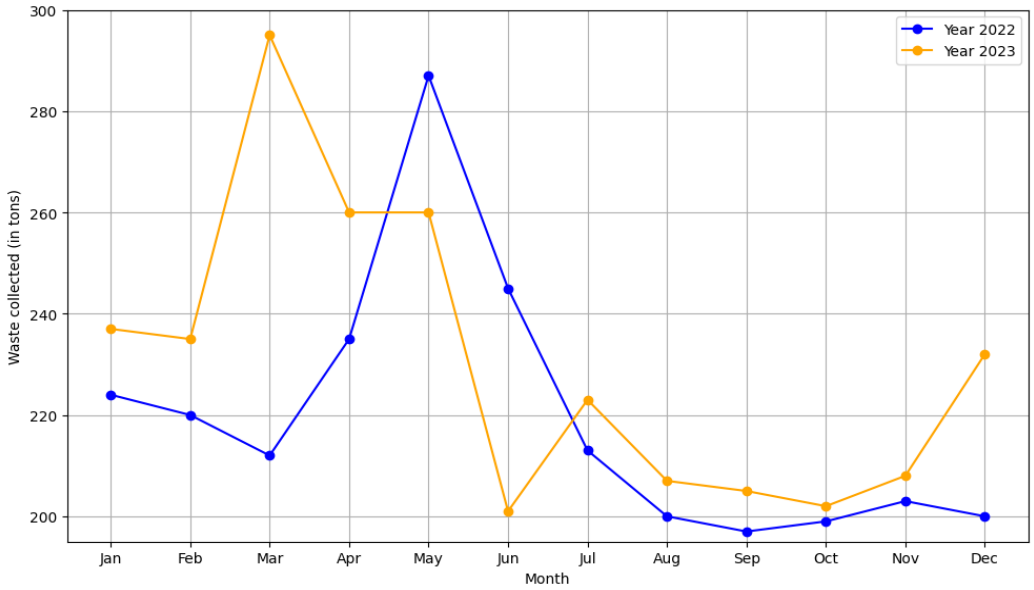

Figure 9. Monthly HSW collection in the municipality of Cheurfa in 2022 and 2023.

3.2.3.3. Monthly tonnages in the municipality of Eulma

HSW collection in Eulma rose by 4.6%, from 3,364 tonnes in 2022 to 3,520 tonnes in 2023 (+156 tonnes). Summer months recorded the highest volumes, particularly July and August 2023 (349 and 373 tonnes, respectively), yielding a ratio of 0.73 kg/inhabitant/day. September and October recorded the lowest volumes (206 and 210 tonnes, respectively). In 2022, the peak was in July (348 tonnes), while September recorded the lowest volume (197 tonnes), with a generation ratio of 0.71 kg/inhabitant/day (Fig. 10).

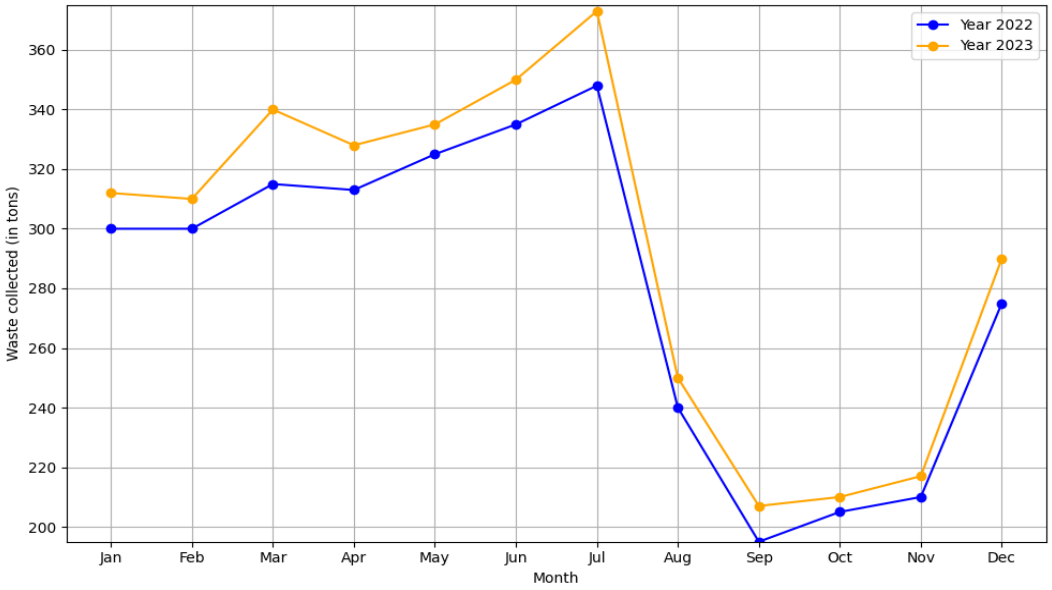

Figure 10. Monthly HSW collection in the municipality of Eulma in 2022 and 2023.

3.2.4. Annual HSW tonnage in the three inland districts

HSW collection across the three districts showed an overall increase between 2022 and 2023. El Hadjar's annual tonnage rose from 40,266 to 41,495 tonnes (+3.05%). The district of Berrahal showed a larger increase, with annual collection rising from 19,661 to 22,404 tonnes (+13.95%), notably driven by the exceptional growth recorded in Oued Aneb. The district of Ain Berda saw a more moderate increase, reaching 13,625 tonnes in 2023 compared with 13,128 tonnes in 2022 (+3.78%). Overall, the three districts produced 73,055 tonnes in 2022 and 77,524 tonnes in 2023, representing a total increase of 6.12% (Fig. 11).

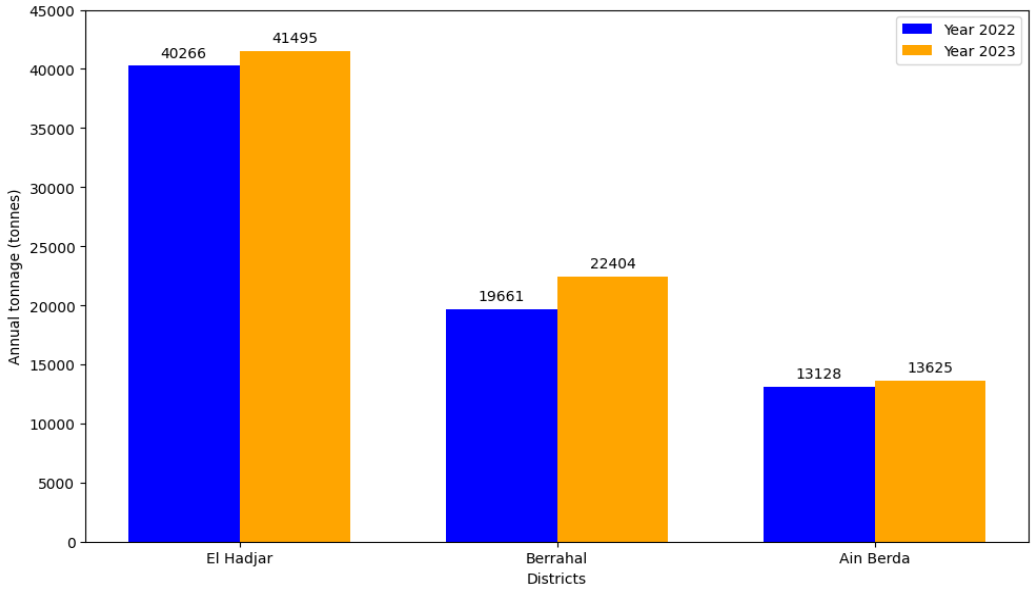

Figure 11. Annual HSW collection in the three inland districts of the wilaya of Annaba in 2022 and 2023.

3.3. Correlation between population size and HSW production

To test the research hypothesis, a Pearson correlation analysis was performed using commune-level data (n = 8 communes) for both 2022 and 2023. Table 4 summarizes the population estimates, annual HSW tonnages, generation ratios, and HSW growth rates for all eight communes.

Table 4. Population, HSW production, and generation ratios by commune (2022–2023)

Commune	Population 2022	HSW 2022 (tonnes)	HSW ratio 2022 (kg/inhab./day)	Population 2023	HSW 2023 (tonnes)	HSW ratio 2023 (kg/inhab./day)	HSW growth (%)
El Hadjar	42,949	11,831	0.75	43,378	12,274	0.78	+3.75
Sidi Amar	101,143	28,435	0.77	102,559	29,221	0.78	+2.76
Berrahal	29,861	9,598	0.88	30,458	10,067	0.91	+4.89
Oued Aneb	27,825	8,024	0.79	28,382	10,239	0.99	+27.61

Tréat	7,800	2,039	0.72	7,940	2,098	0.72	+2.89
Ain Berda	26,097	7,130	0.75	26,541	7,338	0.76	+2.92
Cheurfa	10,589	2,634	0.68	10,642	2,767	0.71	+5.05
Eulma	13,062	3,364	0.71	13,284	3,520	0.73	+4.64

The Pearson correlation coefficient between commune population size and annual HSW tonnage reached $r = 0.9998$ ($p < 0.001$) for 2022 and $r = 0.9992$ ($p < 0.001$) for 2023, confirming a near-perfect positive linear relationship. The coefficient of determination ($R^2 = 0.9996$) indicates that population size explains more than 99.9% of the variance in annual HSW production across communes. The linear regression model for 2022 yielded: HSW (tonnes/year) = 0.274 × Population + 66.8, suggesting that each additional 1,000 inhabitants generates approximately 274 additional tonnes of HSW per year under current conditions.

However, the commune of Oued Aneb constitutes a notable outlier, with a 27.6% increase in HSW tonnage between 2022 and 2023 despite a population growth rate of only 2.0%. This anomaly is likely attributable to an extension of formal municipal collection coverage within the commune rather than a sudden change in per capita waste generation, and does not affect the overall validity of the correlation.

Generation ratios ranged from 0.68 kg/inhabitant/day (Cheurfa) to 0.99 kg/inhabitant/day (Oued Aneb in 2023), and from 0.68 to 0.88 kg/inhabitant/day when excluding the Oued Aneb outlier for 2023. This inter-communal variability reflects differences in urbanization level, commercial activity density, and proximity to the urban centre of Annaba.

3.4. Morphological composition of HSW in the three inland districts

Analysis of the morphological composition of HSW in the three districts studied reveals a dominant proportion of organic matter, accounting for 57% of the total. This majority fraction reflects the essentially biodegradable nature of the waste generated by residents and is consistent with the food-oriented consumption habits prevailing in the study area. Complex compounds constitute 21% of the waste stream, comprising heterogeneous composite materials difficult to recycle due to their multi-component nature (multi-layer packaging, synthetic foams, technical textiles, etc.). Plastics represent 15% of the total flow, reflecting significant consumption of polymer-based food packaging and consumer products.

Paper and cardboard account for only 5% of the waste collected , a markedly low figure that can be attributed to informal upstream recovery, whereby waste collectors and scrap dealers systematically divert paper and cardboard before formal municipal collection. This sector is discussed further in Section 4. Metals and glass are each represented at less than 1%, likewise reflecting their systematic recovery through parallel informal circuits prior to official collection (Fig. 12).

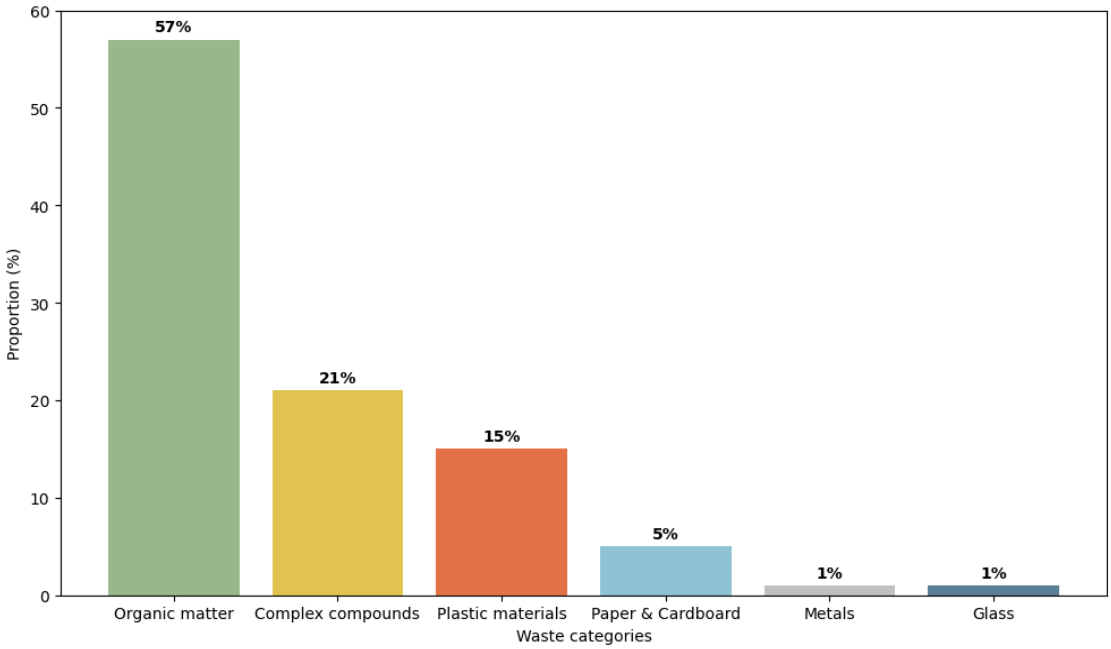

Figure 12. Morphological composition of municipal solid waste in the three inland districts of Annaba.

4. Discussion

Global demographic change has accelerated at an unprecedented rate in recent decades. The world population is projected to rise from 7.7 billion in 2019 to 9.7 billion in 2050 and 10.9 billion in 2100, with growth particularly pronounced in sub-Saharan Africa and North Africa (Arsenović, 2024; Bongaarts, 2016). Since independence in 1962, Algeria's population has tripled, rising from approximately 11 million to over 45 million in 2023, driven by improved living conditions, reduced infant mortality, and persistently positive natural population increase despite recent fertility decline (ONU, 2023; Ouadah-Bedidi & Vallin, 2013).

The demographic dynamics observed in the three inland districts of Annaba , sustained growth in El Hadjar, moderate peri-urban expansion in Berrahal, and slower agricultural-area growth in Ain Berda , are consistent with broader urbanization patterns documented across the Maghreb. El Hadjar's particularly strong growth is directly linked to the presence of steel production activities (ArcelorMittal plant), which generates substantial labor demand and attracts in-migration (Saidi et al., 2024). Similar industrial-urbanization linkages have been observed in comparable contexts, such as the city of Marrakech in Morocco (Aboulaiche & Gallad, 2023) and peri-urban zones around Algerian metropolitan centers (Bounoua et al., 2023). The moderate, stable growth of Ain Berda parallels patterns observed in other Mediterranean agricultural hinterlands, where rural planning policies contribute to population retention (Van der Ploeg et al., 2015).

The near-perfect positive correlation between commune population size and annual HSW production ($r = 0.9998$, $p < 0.001$) confirms the central hypothesis of this study and is consistent with the findings of comparable research. The average HSW generation ratio of 0.68–0.99 kg/inhabitant/day aligns closely with the World Bank's benchmark for lower-middle-income countries (0.74 kg/capita/day) (Kaza et al., 2018). Similar ratios have been documented in other Algerian municipalities: Cheniti et al. (2020) reported ratios of 0.78–0.85 kg/inhabitant/day in the city of Annaba itself, while Bensmail & Bouzadi (2021) reported comparable values in Bejaia. The linear regression model derived from commune-level data ($HSW \approx 0.274 \times Population + 66.8$) provides a practical tool for municipal planners to forecast waste volumes as a function of projected population growth.

The observed 6.12% overall increase in collected HSW between 2022 and 2023 exceeds the population growth rate over the same period (~1.4%), suggesting that factors beyond pure population increase , including urbanization of peri-urban areas, expansion of collection coverage, and evolving consumption habits , are also driving waste generation. This pattern mirrors findings from other countries of the Global South, where waste generation typically grows faster than population due to rising standards of living and commercialization of food and packaging (Zhu et al., 2008; Hoornweg & Bhada-Tata, 2012).

The seasonal distribution of HSW flows with production peaks in March–April and July–August, reflects two distinct socio-cultural drivers: (i) the substantial increase in food consumption and packaging use during the holy month of Ramadan, and (ii) the return of summer visitors and intensified tourist activity during the summer months. These findings are consistent with studies conducted in other cities of the Maghreb and the broader developing world, where seasonal patterns linked to religious and climatic cycles significantly influence waste volumes and composition (Hoornweg & Bhada-Tata, 2012; Cheniti et al., 2020). Such fluctuations present a major operational challenge for municipal services, requiring flexible reorganization of logistical and human resources to manage peak loads effectively.

The dominant proportion of organic matter in the waste stream (57%) is characteristic of cities in the Global South, where dietary patterns are strongly oriented toward fresh produce and home-cooked meals (Kaza et al., 2018). This composition is consistent with findings from other Algerian urban contexts (Attalah & Meftah, 2024; Bensmail & Bouzadi, 2021; Cheniti et al., 2020) and highlights a high potential for biological recovery through domestic or semi-industrial composting and anaerobic digestion. However, this potential remains largely underexploited due to the absence of appropriate infrastructure, lack of supportive policy frameworks, and insufficient public awareness.

Conversely, the low share of dry recyclable materials 15% for plastics, 5% for paper and cardboard, and less than 1% each for metals and glass ,is best explained by the activity of the informal waste recovery sector. The informal recovery sector, also referred to in the literature as the "informal recycling economy" or "waste picking," comprises individuals and small enterprises who collect and resell recoverable materials

upstream of formal municipal collection, primarily driven by economic incentive (Medina, 2000). This sector is well documented across developing countries and has been shown to divert substantial fractions of paper, cardboard, metals, and plastics before they reach official collection points. In Algeria, several studies have emphasized the growing role of informal reclaimers (known locally as "chiffonniers") in the urban circular economy, although their integration into official waste management frameworks remains marginal (Hassaine & Abrika, 2023). In the present study, the consistently low proportions of paper, metals, and glass across all three districts provide indirect morphological evidence of active upstream diversion. Formalizing and integrating this sector within municipal waste management systems could significantly improve recycling rates and reduce the burden on public services.

5. CONCLUSIONS

This study has provided an integrated analysis of demographic dynamics and household and similar waste (HSW) management in three inland districts of Annaba Province: El Hadjar, Berrahal, and Ain Berda. The findings support the stated research hypothesis: population growth in these districts is positively correlated with increases in HSW production, as confirmed by a near-perfect Pearson correlation ($r = 0.9998$, $p < 0.001$) between commune-level population size and annual waste tonnage.

Demographic projections indicate significant population increases across all three districts by 2030, with growth rates varying according to territorial specificities: strong urbanization in El Hadjar (linked to industrial employment), peri-urban development in Berrahal (driven by proximity to the Annaba metropolitan area), and more moderate progression in Ain Berda (shaped by agricultural land use). Together, the three districts are projected to add approximately 40,000 inhabitants by 2030 relative to 2020, with direct implications for the volume and management of HSW.

Over the 2022–2023 study period, HSW production increased by 6.12% overall — a rate that exceeds average population growth, pointing to the additional influence of urbanization, expanded collection coverage, and evolving consumption patterns. The linear regression model derived from commune-level data enables forward projection of waste volumes as a function of demographic growth, providing a practical planning tool for local authorities.

HSW characterization demonstrates a strong predominance of organic matter (57%), revealing considerable potential for biological recovery - particularly through composting or anaerobic digestion. The consistently low proportions of dry recyclables (paper, metals, glass) are consistent with morphological evidence of significant upstream material diversion by an active informal recovery sector. Formalizing and integrating this sector represents a strategic opportunity to improve recycling rates without additional public expenditure.

Marked seasonal variations, with production peaks in March–April (Ramadan period) and July–August (summer influx), necessitate flexible adaptation of logistical and human resources dedicated to waste collection and treatment.

In response to these challenges, four strategic recommendations emerge: (1) develop biological recovery infrastructure , composting and biogas facilities , adapted to the dominant organic profile of the waste; (2) formalize and integrate the informal recovery sector within an inclusive, regulated management framework; (3) implement targeted awareness campaigns to encourage source reduction and selective sorting among residents; and (4) adopt prospective waste management planning that explicitly incorporates the demographic and urban expansion projections presented in this study.

This research contributes to understanding the complex interactions between demographic dynamics and waste management in the context of ecological transition in North Africa. The experience of Annaba's inland districts could serve as a reproducible model for other Algerian territories facing similar challenges, providing a pathway toward more integrated and sustainable waste management at the national scale. Future work should address consumption pattern dynamics through dedicated household surveys and extend the temporal scope of both demographic and waste data to enable more robust longitudinal analysis.

Conflict of Interest / Competing interests

The authors declare that there is no conflict of interest.

Consent to Publish

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