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Exploratory Multitechnique Characterization of Soil Contaminants in Underexplored Environments: Evidence from El-Bur in Somalia

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Abstract

Soil contamination in underexplored environments remains poorly characterized, particularly in regions where systematic monitoring is limited. El-Bur (Somalia) represents one such environment, where prolonged drought, humanitarian instability, limited accessibility, and inadequate waste management are expected to influence soil quality while hindering systematic environmental investigations. In this study, an exploratory multi-technique approach was applied to soil samples collected from selected sites in El-Bur (Somalia) to obtain chemical, structural, and morphological information. A combination of SEM–EDX, ICP-OES, XRD, and GC–MS was used to characterize both inorganic and organic fractions. The results show a predominant presence of sodium chloride, indicating severe soil salinity likely associated with prolonged drought and evaporative processes. In addition, trace organic compounds, including plastic-related species such as diethyl phthalate and styrene, together with short- to medium-chain hydrocarbons, were detected, suggesting localized anthropogenic contamination likely related to plastic waste and inadequate wastewater and waste management practices. This work provides a proof-of-concept analytical framework for identifying contamination features in soils affected by severe drought. The findings highlight the coexistence of natural and anthropogenic drivers of soil degradation and provide exploratory evidence for future targeted investigations in underexplored regions.

Keywords: soil salinity; soil contamination; soil health; Somalia; multi-technique analysis

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1. Introduction

Pollution remains a major global health challenge and is estimated to contribute to millions of premature deaths each year, affecting ecosystems, human health, and socioeconomic stability [1]. Among environmental compartments, soils play a critical role by supporting essential ecosystem services, including food production, nutrient cycling, and water regulation. Consequently, soil contamination represents a significant concern for environmental sustainability and public health [2].

Despite increasing attention to soil quality, contamination in underexplored environments remains poorly characterized, particularly in regions where systematic environmental monitoring is limited or absent. This is especially relevant in low-resource and politically fragile settings, where climatic stress, inadequate waste management, and weak regulatory frameworks may favor the accumulation and persistence of contaminants [3,4]. In areas affected by conflict or humanitarian crises, environmental investigations are further hindered by security constraints and restricted access, often resulting in a lack of baseline datasets and limiting the assessment of environmental degradation and contamination pathways [5,6].

In such contexts, soils can act as both sinks and potential sources of exposure, with implications for ecosystems, agriculture, and human health.

In Sub-Saharan Africa, soil degradation and contamination are driven by a combination of natural and anthropogenic factors. Prolonged drought and desertification contribute to soil salinization and structural degradation, while human activities such as artisanal mining, informal waste disposal, combustion processes, and poorly regulated agricultural practices introduce a wide range of contaminants into soils [7–9]. For instance, heavy metal contamination has been reported in mining-affected areas, while pesticide residues and persistent organic pollutants have been detected in agricultural soils [10,11]. In addition, open waste dumping and burning practices contribute to the release of toxic compounds, including dioxins and plastic-derived pollutants, which can accumulate in soils and enter food chains [12–14]. Increasing aridity and groundwater salinity further exacerbate these processes, promoting salt accumulation in surface soils and negatively affecting soil fertility and crop productivity [15,16].

Within this framework, Somalia represents a particularly underexplored case. The country has experienced decades of political instability, weak environmental governance, and recurrent drought, which have limited the development of monitoring systems and the availability of reliable environmental data [17,18]. Although initiatives such as the Somalia Water and Land Information Management project have contributed to the reconstruction of environmental datasets, studies specifically addressing soil contamination remain scarce [13,19]. As a result, the interplay between natural soil properties, climatic conditions, groundwater quality, and anthropogenic inputs is still poorly understood [20,21].

These limitations are particularly evident in central Somalia, where prolonged drought and internal displacement have significantly altered settlement patterns and increased pressure on fragile environments [22,23]. The importance of establishing baseline environmental datasets in conflict-affected regions has recently been highlighted as a prerequisite for assessing contamination, identifying environmental risks, and supporting future remediation and monitoring activities [5,6].

El-Bur, located in the Galmudug region, is characterized by arid to semi-arid conditions, low and irregular rainfall, saline groundwater, and limited information on waste and wastewater management [20,24]. In addition, the presence of internally displaced populations in urban and peri-urban areas may contribute to environmental stress through inadequate sanitation and uncontrolled waste disposal [25]. Under such conditions, distinguishing between natural soil degradation processes, such as salinization driven by evaporative dynamics, and superimposed anthropogenic contamination becomes particularly challenging.

In this study, an exploratory multi-technique analytical approach was applied to soil samples collected in El-Bur, Somalia, with the aim of investigating the nature and possible sources of soil contamination in a poorly characterized environment. By integrating scanning electron microscopy, energy-dispersive X-ray analysis, inductively coupled plasma optical emission spectroscopy, X-ray diffraction, and gas chromatography–mass spectrometry, both inorganic and organic fractions of the samples were characterized. To the best of our knowledge, this represents one of the first studies to combine complementary structural, elemental, and chemical analytical techniques for the integrated characterization of soils from central Somalia. The novelty of this work lies not only in providing the first comprehensive baseline dataset for this underexplored region, but also in demonstrating an analytical workflow capable of distinguishing between natural salinization processes and localized anthropogenic contamination. This integrated framework may be applied to other arid and resource-limited environments where environmental monitoring is limited or absent. The study is conceived as an exploratory investigation designed to provide initial evidence and support future, more spatially resolved studies in underexplored regions.

2. Materials and Methods

2.1. Study Area

Soil samples were collected in a central city in Somalia. Somalia, located at the easternmost point of the Horn of Africa, is bordered by Kenya to the southwest, Ethiopia to the west, and Djibouti to the northwest and has coastlines along the Gulf of Aden to the north and the Indian Ocean to the east. The country is administratively divided into six proposed regional states: Somaliland, Puntland, Galmudug, Jubaland, South West State, and Hir-Shabelle [26].

Soil sampling was carried out in January 2023 in El-Bur city (coordinates 4.6840005, 46.6196177), located in the Galmudug Regional State in central Somalia. El-Bur lies on the central plateau, which spans approximately 150,000 km^2, corresponding to about one-fourth of the country's total area. The city is situated approximately 360 km northwest of Mogadishu, at an average elevation of 175 m above sea level [24].

Figure 1 shows the location of Somalia and the sampling area.

The landscape surrounding El-Bur is predominantly flat to slightly undulating and is characterized by playas, seasonal saline lakes, and ephemeral rivers. The region is classified as arid to semi-arid, with annual rainfall generally not exceeding 200 mm and often falling below this threshold, particularly during prolonged drought periods such as 2020–2023. Soils are mainly classified as alkaline Petric or halic Gypsisols, characterized by moderate to high salinity and generally unsuitable for agriculture, although they may support limited grazing [8].

Water supply in the area relies on boreholes, shallow wells, and rainwater harvesting systems. According to World Bank data [20], only one out of ten analyzed boreholes meets safety criteria for human consumption. In addition, no structured information on waste management is currently available for El-Bur, where disposal practices likely rely on informal dumping or burning. The combination of naturally high soil salinity, saline groundwater, arid climate, and limited waste management infrastructure may significantly influence soil properties. These conditions make soils from El-Bur particularly suitable for investigating the interplay between natural processes and potential anthropogenic contributions to soil degradation.

2.2. Sampling and Analytical Methods

In order to investigate soil properties, a total of three samples were collected at a depth of 0–10 cm from selected locations within the urban area of El-Bur. The sampling sites included the central market area, a main road crossing the western part of the city, and a less populated north-eastern district.

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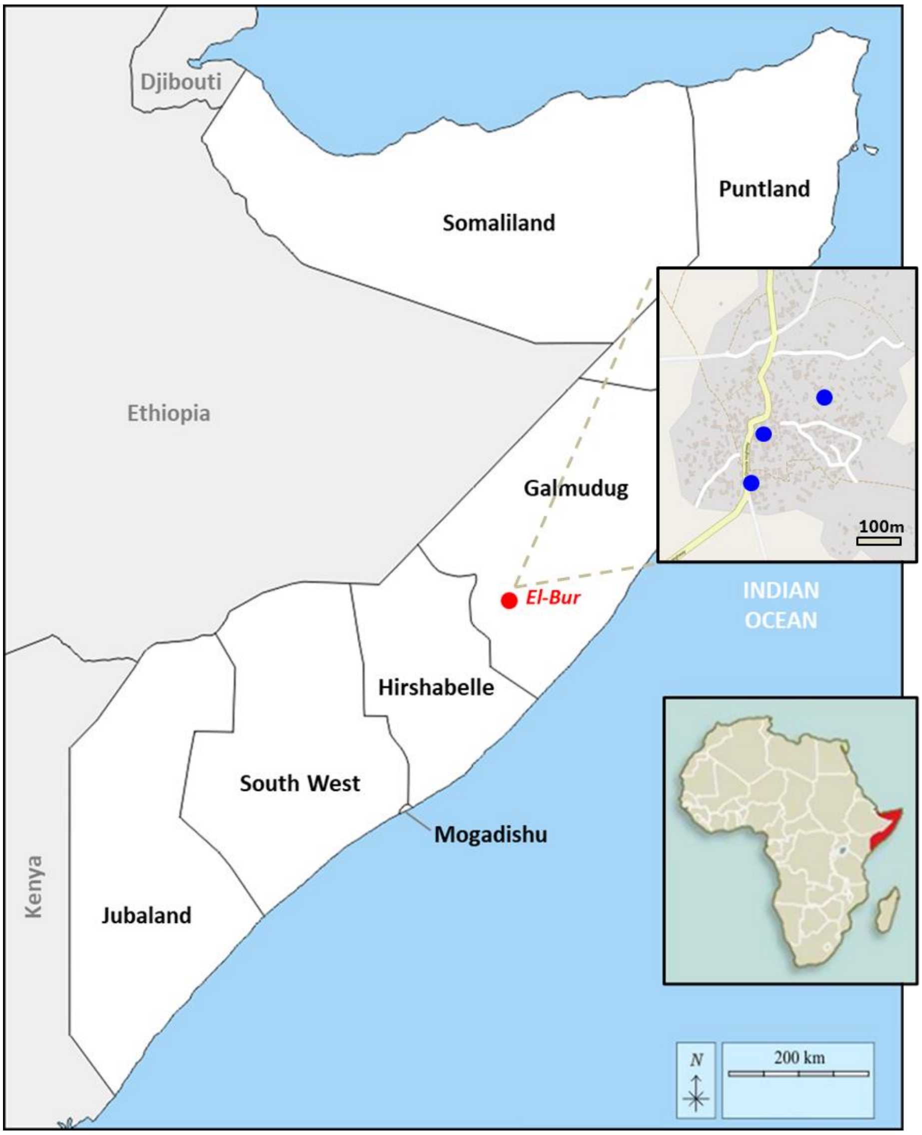

Figure 1. Location, borders, and administrative regions of Somalia. The red dot indicates the town of El-Bur and the blue dots the sampling sites in the city's residential regions (maps adapted from https://d-maps.com, 2025).

These locations were selected to represent different urban settings potentially influenced by varying degrees of anthropogenic activity, including commercial, traffic-related, and residential environments. The sampling strategy was designed to explore site-to-site variability within the study area, without aiming at statistical representativeness. The objective of the sampling campaign was to obtain an initial characterization of the surface materials present in different urban contexts rather than to provide a statistically representative evaluation of spatial variability. The collected material consisted of soil aggregates emitting a distinct odor. Samples were manually collected using clean sampling tools, avoiding visible debris and external contamination during collection. Samples were stored in sealed glass tubes and kept at room temperature until laboratory analysis.

As a first step, the chemical composition of the soil was determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The samples were dried overnight at 105 °C to remove moisture and ensure accurate gravimetric measurements prior to digestion. Subsequently, 250 mg of each sample were completely dissolved in 4 mL of HNO_3 (65%, VWR Chemicals) to solubilize the acid-extractable inorganic fraction for ICP-OES analysis in separate 50 mL flasks and diluted to volume with deionized water. The resulting solutions were analyzed using an ICP-OES instrument (AVIO 220 Max, PerkinElmer Inc.). Calibration curves were prepared using appropriate dilutions of a certified multielement standard solution (Ag, Al, B, Ba, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, In, K, Li, Mg, Mn, Na, Ni, Pb, Sr, Tl, Zn; 1000 mg/L; Merck Certipur, Merck KGaA, Darmstadt, Germany.

The crystallographic phases of the collected pebbles were characterized by X-ray diffraction (XRD) using an X'Pert PRO diffractometer (Philips, now Malvern Pananalytical Ltd Malvern, UK) with CuKα radiation (λ = 0.154 nm). Selected pebbles from each sample were ground to obtain a homogeneous powder and deposited on a silicon substrate. Diffraction patterns were acquired in θ–θ geometry over a 5–90° (2θ) range. Phase identification was performed using QUALX software ver 2.24 [27] in combination with the POW_COD database [28].

Surface morphology was investigated by Scanning Electron Microscopy (SEM) using a SUPRA™ 35 instrument (Carl Zeiss SMT, Oberkochen, Germany) operating at 7 keV. Elemental analysis was carried out by Energy-Dispersive X-ray (EDX) spectroscopy using an INCAx-sight system (Oxford Instruments, High Wycombe, HP12 3SE, UK coupled to the SEM and operated at 20 keV.

The organic fraction was analyzed by GC–MS following solvent extraction. The extraction was carried out according to a previously validated laboratory protocol. The extraction was carried out at 60 °C in an oil bath for a total duration of 24 h, conditions selected to enhance the recovery of volatile and semi-volatile organic compounds while minimizing their thermal degradation. After extraction, all solutions were concentrated under a gentle stream of nitrogen, transferred into 1.5 mL vials, and spiked with a certified internal standard (100 ng/mL, toluene-d8, Dr. Ehrenstorfer, Augsburg, Germany, ISO 17034) to enable reliable semi-quantitative analysis and correct for instrumental variability.

GC–MS analyses were performed using a triple quadrupole gas chromatograph/mass spectrometer system (1310 GC coupled to TSQ 8000 Evo, Thermo Scientific, Waltham, MA, USA). Chromatographic separation was achieved using a DB-XLB capillary column (60 m × 0.25 mm I.D., Agilent J&W, Santa Clara, CA, USA), with hydrogen as the carrier gas at a constant flow rate of 3 mL/min. A volume of 1 µL was injected in splitless mode at an injector temperature of 250 °C.

The oven temperature program consisted of an initial isothermal step at 90 °C for 5 min, followed by a ramp of 10 °C/min up to 280 °C, held for 5 min. The mass spectrometer was operated in positive electron ionization mode (EI+, 70 eV) with an emission current of 50 µA. Data acquisition was performed in full scan mode over a mass range of 35–450 m/z, with a scan time of 0.2 s. The transfer line and ion source temperatures were set at 290 °C and 300 °C, respectively.

Quality assurance and quality control (QA/QC) procedures included analysis of procedural blanks, replicate measurements, and samples spiked with certified reference materials. Compound identification was performed using Xcalibur 2.2 software (Thermo Fisher Scientific, Waltham, MA, USA) by comparison with the NIST/EPA/NIH mass spectral library (NIST 08).

A semi-quantitative estimation of compound concentrations was obtained by calculating peak area ratios relative to the internal standard (toluene-d8), allowing a comparative assessment of the detected species.

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3. Results and Discussion

3.1. Soil Composition and Morphology

In January 2023, soil samples were collected from selected locations within the urban area of El-Bur (Somalia) in order to investigate soil composition and identify potential contamination features. The collected samples exhibited variability in size and showed a faint pink coloration (Figure S1 in the Supplementary Information). In difficult-access environments, where extensive sampling campaigns may be limited by logistical, security, or financial constraints, maximizing the information obtained from each collected sample becomes essential. In this context, the integration of complementary analytical techniques represents an effective strategy, allowing multiple aspects of soil composition and contamination pathways to be investigated from a limited number of samples. Although such an approach cannot replace large-scale monitoring programs, exploratory studies based on carefully selected samples can provide valuable baseline information, identify priority contaminants or degradation processes, and support the design of future spatially and temporally resolved investigations.

The results obtained from the complementary analytical techniques are presented below. SEM–EDX, ICP-OES, and XRD were used to characterize the inorganic fraction of the samples, whereas GC–MS was employed to investigate the extracted organic compounds. The integration of these techniques provides the basis for the interpretation of both natural soil characteristics and potential anthropogenic contamination.

Figure 2 displays the results of the EDX analysis, showing that chlorine (35.93 ± 0.060 at%) and sodium (37.42 ± 0.110 at%) are the predominant elements in the analyzed sample, consistent with halite-dominated material. Carbon (8.68 ± 0.090 at%) and oxygen (15.05 ± 0.100 at%) are also present, although at lower relative abundances. In addition, sulfur (0.74 ± 0.0005 at%), magnesium (1.90 ± 0.010 at%), silicon (0.09 ± 0.005 at%), copper (0.05 ± 0.005 at%), potassium (0.10 ± 0.005 at%), calcium (0.04 ± 0.005 at%), and neodymium (0.01 ± 0.005 at%) are detected at trace levels. ICP-OES analysis was focused on the major elements contributing to the inorganic composition identified by SEM–EDX. Other elements were not quantified because they were below detection limits.

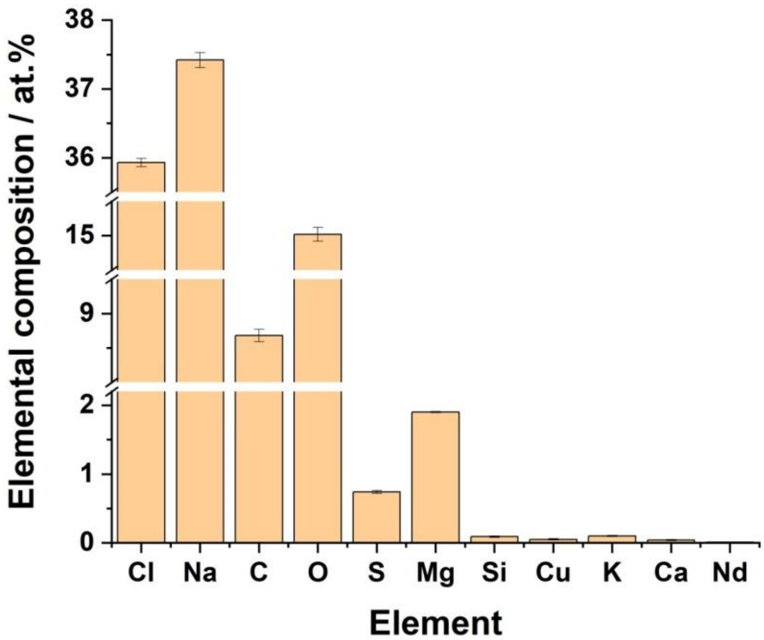

Figure 2. EDX elemental analysis (at%) of soil sampled in El-Bur, Somalia.

ICP-OES analysis was performed to complement the EDX results, particularly to assess the presence of light elements such as lithium, which cannot be reliably detected by EDX, and to verify the elemental composition of the samples. Table 1 reports the concentrations expressed as %wt/%wt of the quantified elements, confirming the trends observed in the EDX analysis. Lithium, if present, was found to be below the detection limit (<0.001 wt%). Elements of environmental concern, such as cadmium, chromium, and lead, were not detected in the analyzed samples.

Table 1. Chemical composition of soil sampled in El-Bur, Somalia, estimated by ICP-OES.

Element	Average Value [mg/g]	Std. Dev. [mg/g]	Average Value [%wt/%wt]	Std. Dev. [%wt.]
Na	262.10	6.70	26.20	0.60
Mg	4.16	0.52	0.42	0.05
Cu	<0.01		<0.001	
K	1.98	0.16	0.19	0.02
Ca	2.28	0.19	0.23	0.02
Li	<0.01		<0.001	

In Figure 3, reporting the concentrations of the most relevant elements (>0.001 wt%), the dominant contribution of sodium to the chemical composition of the soil material is further highlighted.

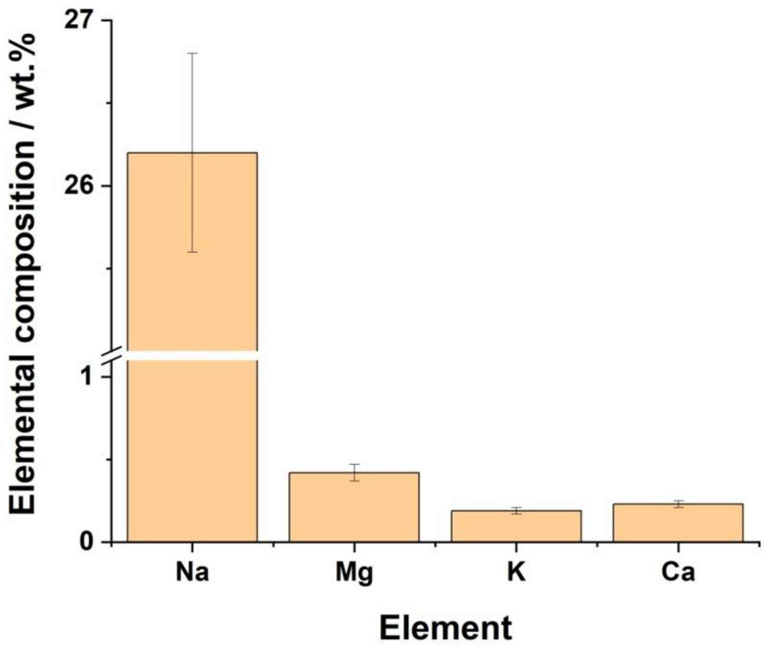

Figure 3. Mean concentrations (%wt) of the most relevant elements (>0.001%wt) as estimated from ICP-OES analysis.

The XRD analysis of the soil is reported in Figure 4 (black). The pattern, obtained using Cu target radiation, shows a very high correspondence with cubic NaCl (halite) structure [29], with excellent correspondence in peak location and intensity [27].

More specifically, peaks are observed at 27.7 2-theta degrees, corresponding to 111 crystal plane diffraction, 32.1 (200), 45.7 (220), 54.3 (311), 56.7 (222), 66.5 (400), 75.5 (420) and 84.3 (422). The two patterns (investigated samples and halite mineral reference) are juxtaposed in Figure 4, where an excellent superposition can be noticed, pointing out both a high degree of crystallinity of the soil sample and a very close match in their structural composition.

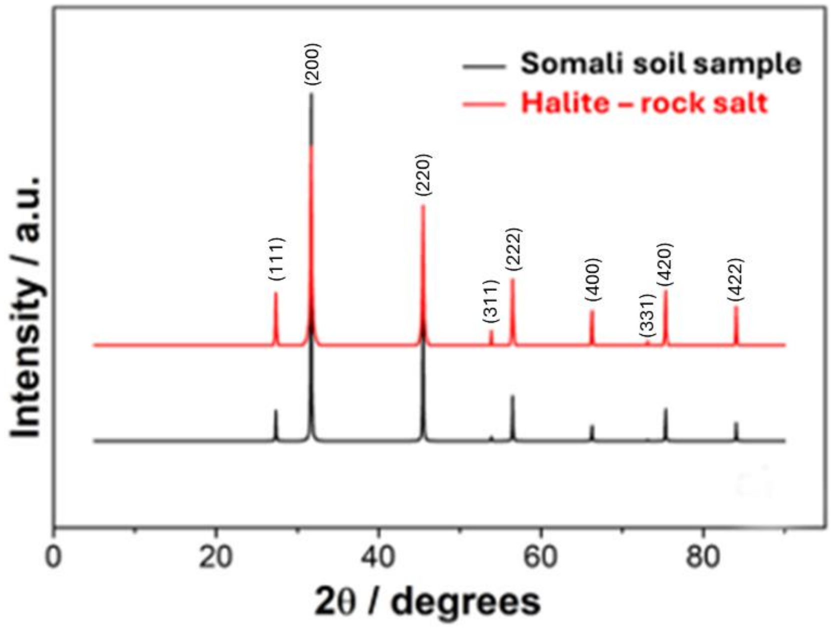

Figure 4. Soil sampled in El-Bur, Somalia: black solid line, XRD pattern of the sample, and red line, Halite (rock salt).

From an environmental perspective, the dominance of halite indicates strong evaporative concentration processes typical of arid environments. In the investigated area, upward migration of saline groundwater followed by evaporation may promote secondary salt accumulation at the surface. Considering that other structures of the same shape but different composition (e.g., Cu_2S) have lower correspondence in the peak position and intensities and that no additional peaks were noticed that could suggest a sizeable inclusion of other phases, the structure was confidently assigned as halite based on the excellent agreement with the reference pattern. However, the possible presence of minor phases such as quartz, feldspars, carbonates, or clay minerals below the XRD detection limit cannot be excluded. These findings may not exclude minor contributions from other soil components lying below the XRD detection limit. XRD analysis revealed no evidence of an amorphous phase below 20 degrees, indicating the absence of solid carbonaceous materials. The reported uncertainties include analytical repeatability from replicate measurements.

The predominant presence of halite in the analyzed samples is further supported by morphological observations obtained by SEM (Figure 5). The images show that the material mainly consists of cubic particles, characteristic of halite (rock salt), as indicated by the arrows. No grinding was performed prior to SEM analysis, ensuring that the observed morphology reflects the native structure of the collected material.

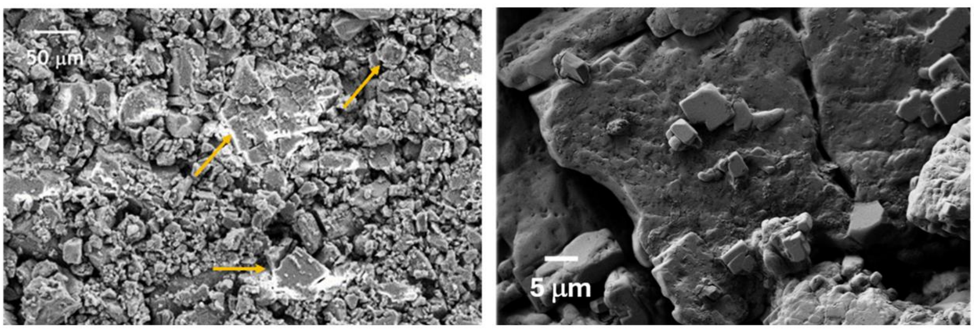

Figure 5. Soil sampled in El-Bur, Somalia: selected SEM images at 200 X magnification (**left** panel) and 5 K X magnification (**right** panel). The yellow arrows indicate cubic NaCl particles.

The size of the halite agglomerates ranges between 20 and 50 µm, indicating a relatively coarse structure. In addition, smaller particles, on the order of 1 µm, are also observed.

The results obtained from the different analytical techniques are mutually consistent: the cubic morphology observed by SEM, the Na–Cl-dominated elemental composition measured by EDX and ICP-OES, and the crystallographic match obtained by XRD collectively confirm the halite-rich nature of the investigated materials.

3.2. Organic Traces in the Soil

Given the potential presence of additional compounds, particularly in light of the distinctive scent emitted by the soil samples, further investigation of the organic fraction was undertaken. To identify and characterize these substances, a series of extractions was performed using five solvents with different polarities: chloroform, ethyl acetate, hexane, methanol, and petroleum ether. This multi-solvent approach was designed to cover a broad polarity range and to enable the extraction of compounds with diverse chemical characteristics.

By employing solvents of varying polarity, the procedure aimed to capture a wide spectrum of organic compounds, including both volatile and semi-volatile species, as well as trace-level components. This strategy increases the likelihood of detecting compounds associated with different potential sources and environmental processes. The subsequent GC-MS analysis enabled the identification of compounds present in the soil extracts, as reported in Table 2. The reported concentrations should be considered semi-quantitative estimates rather than absolute quantitative measurements.

Table 2. Compounds extracted from soil sampled in El-Bur, Somalia, with methanol, hexane, petroleum ether, chloroform, and ethyl acetate. Compounds found in at least three extraction solvents are reported in bold light blue and are marked with a *.

Compound	Methanol	Hexane	Petroleum Ether	Chloroform	Ethyl Acetate
1,3:2,4-di-O-benzylideneribitol	✓		✓		✓
1-Chlorodecane	✓				
2,2,6-Trimethyloctane		✓			
2,2-Dimethoxybutane					✓
2,3-Dimethylhexane				✓	
2,4-Dimethylhept-1-ene *		✓	✓	✓	
2,4-Dimethylheptane		✓		✓	
3,3-Dimethyloctane		✓			
4-Hydroxy-3-methoxyphenylacetate					✓
4-Hydroxybenzenecarboxylic acid					✓
4-Methylheptane		✓			
4-Methyloctane		✓			
Biphenyl	✓				
Bromobenzene		✓			
Decane					✓
Diethyl phthalate *	✓	✓	✓		
Ethylbenzene				✓	
Hexan-2-one *		✓	✓	✓	
3-Methylundecane *		✓	✓	✓	
Methyl 10-methylundecanoate	✓				
Methyl 2-(1,1-dimethylethyl)-2-methylpropanoate *	✓	✓	✓	✓	
Methyl butanoate	✓				
Methyl decanoate	✓				
Methyl heptanoate	✓				
Methyl hexanoate	✓				

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Table 2. Cont.

Compound	Methanol	Hexane	Petroleum Ether	Chloroform	Ethyl Acetate
Methyl nonanoate	✓				
Methyl octanoate	✓				
Nonane		✓			
Octane		✓			
Styrene *		✓	✓	✓	
Undecane					✓

The distribution of the identified compounds among the different extraction solvents reflects their different chemical properties and extraction affinities. Several compounds were consistently detected in multiple solvents, including diethyl phthalate, styrene, 2,4-dimethylhept-1-ene, hexan-2-one, 3-methylundecane, and methyl 2-(1,1-dimethylethyl)-2-methylpropanoate, suggesting their presence in the soil matrix rather than being isolated extraction artifacts. Among these compounds, styrene and diethyl phthalate are particularly relevant due to their association with plastic-derived materials, whereas aliphatic hydrocarbons may originate from both anthropogenic sources and natural organic matter degradation. Other detected compounds, such as 1,3:2,4-di-O-benzylideneribitol, may have a biological origin. The coexistence of compounds with different chemical signatures suggests the contribution of multiple sources to the organic fraction of the investigated soils.

3.3. Comprehensive Evaluation of Soil Quality

The characterization of soil samples from El-Bur provides insight into the combined influence of environmental and anthropogenic factors affecting soil quality in this arid region. The integration of mineralogical, elemental, and organic analyses allows the contribution of natural processes, such as salinization, to be distinguished from potential anthropogenic contamination pathways, with implications for soil degradation and environmental management. The characterization of the investigated samples through a multi-technique approach reveals a system affected by both environmental and anthropogenic pressures. The analyzed material is overwhelmingly dominated by rock salt, with only minor contributions from other elements, while also showing the presence of organic compounds attributable to external contamination sources. This dual signature highlights the coexistence of natural salinization processes and superimposed anthropogenic inputs.

XRD analysis (Figure 4) shows a highly crystalline structure, with an excellent match to halite and no detectable amorphous contribution. The absence of amorphous phases is particularly relevant, as it suggests a negligible presence of carbonaceous or poorly ordered mineral components typically associated with more developed or fertile soils. This structural evidence is supported by morphological observations. SEM images (Figure 5) reveal predominantly cubic particles, consistent with halite crystallization. Similar euhedral to subhedral cubic morphologies have been previously associated with halite formation in surface crusts or efflorescences [30]. In addition, the occurrence of smaller cubic crystallites on larger agglomerates, as reported by Eswaran et al. [31] for saline soils in arid and semi-arid regions, is consistent with the features observed in the present samples, suggesting the development of surface salt crusts.

Elemental analysis further corroborates this interpretation. EDX results (Figure 2) indicate that sodium and chlorine are the dominant elements in the samples, while ICP-OES data (Table 1 and Figure 3) confirm the overwhelming contribution of sodium to the bulk composition. Additional elements, including magnesium, sulfur, silicon, copper, potassium, calcium, and neodymium, are present only at trace levels. The presence of Mg, Ca, and K is consistent with the incorporation of minor ions during precipitation of saline minerals from evaporating solutions. Silicon may reflect minor residual silicate particles, while sulfur and calcium may be associated with secondary sulfate phases commonly occurring in saline environments. The very low concentration of copper does not indicate a significant anthropogenic metal contamination signal in the investigated materials. These minor constituents may contribute to secondary features such as the observed coloration [15] but do not significantly alter the overall mineralogical framework.

The occurrence of halite-rich aggregates at the soil surface is particularly noteworthy. Previous investigations in the El-Bur area reported that surface layers (0–40 cm) are mainly composed of silicates and carbonates, with halite typically occurring at greater depths [24]. The predominance of halite in the present samples therefore suggests active salt accumulation at the surface. This can be explained by efflorescence processes, whereby saline groundwater rises through capillary action and subsequently evaporates, leading to precipitation of chloride salts at the air–soil interface [32]. The presence of minor elements such as Si, Mg, Ca, K, and Cu within the halite matrix is consistent with incorporation of trace components during crystallization.

Despite the detection of these additional elements, no toxic ions of major environmental concern, such as lead, cadmium, chromium, or arsenic, were identified in the samples, in agreement with WHO guidelines [33]. This suggests that, at least for the inorganic fraction, contamination by heavy metals is not a dominant issue in the investigated material.

The observed salinity is consistent with regional hydrogeochemical conditions. Elevated sodium levels in groundwater have been previously reported as a major driver of soil salinization in the area [34]. Approximately 80% of Somalia's population relies on groundwater, yet only a limited fraction of the groundwater meets recommended electrical conductivity (EC) thresholds for safe consumption [35]. Measurements in El-Bur indicate EC values ranging between 2110 and 3510 µS/cm [20,36]), exceeding WHO recommendations and confirming the presence of highly saline water resources. Hydrogeochemical studies in central Somalia [37] further indicate that groundwater is dominated by dissolved salts such as Na^{+}–Cl^{-} and Ca^{2+}–Mg^{2+}–Cl^{-}–$SO_4{}^{2-}$ systems, consistent with the elemental composition observed in the present study.

In this context, the use of saline groundwater for domestic purposes, livestock, and irrigation may contribute to further salt accumulation at the soil surface. Similar processes have been documented in semi-arid environments, where irrigation practices can significantly increase salinity in the upper soil layers [38]. The preferential accumulation of Na^{+} and Mg^{2+} in topsoil, as observed in the present samples, is consistent with these mechanisms.

The high salinity of the soil has important implications for its functionality. Accumulation of soluble salts such as sodium chloride induces osmotic stress, limits water availability, and disrupts nutrient uptake, ultimately impairing plant growth and agricultural productivity [39,40]. In addition, elevated sodium concentrations can lead to displacement of calcium and magnesium ions, destabilization of soil aggregates, and reduced permeability [41,42]. These processes contribute to soil structure degradation and reduced infiltration capacity, further exacerbating the effects of drought conditions.

Taken together, these observations indicate that the extreme salinity observed in the analyzed materials from El-Bur results from a combination of natural factors—such as arid climate, groundwater composition, and soil-forming processes—and anthropogenic contributions, including water use practices and land management. This combined effect leads to a progressive degradation of soil quality, with consequences not only for agricultural productivity but also for infrastructure stability and long-term environmental sustainability [34].

The estimated concentrations of styrene and diethyl phthalate (DEP) are significantly lower than the tolerable levels reported for soils, i.e., 0.68 ng/mg for styrene and

13,733 ng/mg for total phthalates, according to WHO, 2013 [33]. However, these values should be interpreted in the context of the specific environmental conditions of the sampled material. The analyzed compounds are associated with halite-rich surface crusts exposed to prolonged drought, high temperatures, and intense UV irradiation. Such conditions are known to promote degradation and volatilization of hydrocarbons, likely contributing to the relatively low concentrations observed.

Despite these low absolute values, the relative distribution of compounds suggests a consistent pattern. In particular, the presence of 2,4-dimethylhept-1-ene, DEP, and methyl 2-(1,1-dimethylethyl)-2-methylpropanoate indicates a trend toward the accumulation of contaminants commonly associated with plastic-related sources (Figure 6).

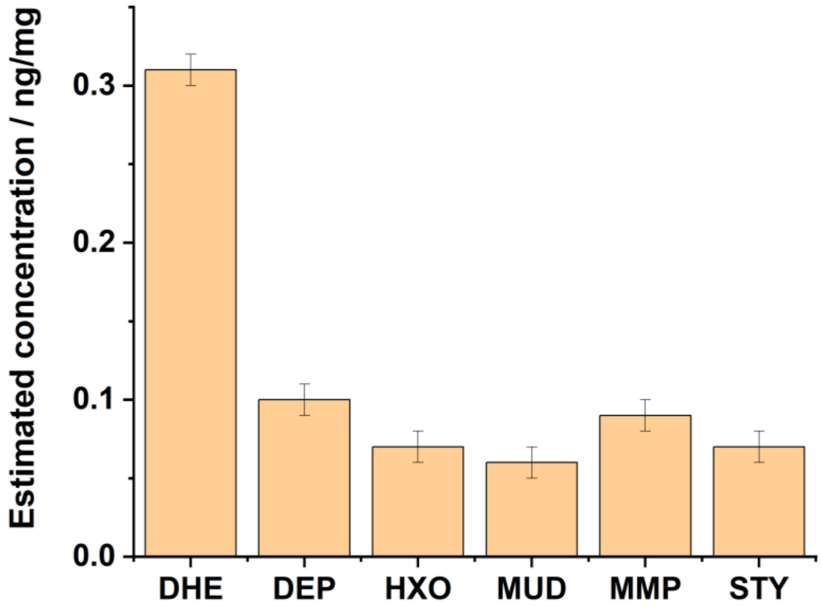

Figure 6. Estimated concentration of the organic contaminants 2,4-dimethylhept-1-ene (DHE), diethyl phthalate (DEP), hexan-2-one (HXO), 3-methylundecane (MUD), methyl 2-(1,1-dimethylethyl)-2-methylpropanoate (MMP) and styrene (STY).

The identification of styrene and 2,4-dimethylhept-1-ene suggests a possible link with plastic waste, as these compounds are commonly associated with polystyrene (PS) and polypropylene (PP), respectively [43,44]. These polymers are extensively used in food packaging and consumer products due to their durability and low cost, but they also represent major contributors to persistent environmental pollution. Although microbial degradation of styrene can occur under aerobic conditions, this process may itself contribute to soil contamination through intermediate products [45,46]. Chronic exposure to styrene has been associated with neurotoxicity, hematological effects, genetic damage, and carcinogenicity [47–49].

DEP, detected in several extraction solvents, is a widely used plasticizer in materials such as PVC and polyethylene terephthalate, as well as in personal care products, industrial goods, and pharmaceuticals [50,51]. The presence of methyl 2-(1,1-dimethylethyl)-2-methylpropanoate, previously reported as a tracer of tobacco smoke residues in indoor dust [52], suggests additional airborne or anthropogenic inputs. Hexan-2-one, another identified compound, is typically associated with waste disposal sites and contaminated water streams and is known for its neurotoxic effects upon prolonged exposure [53].

Alongside these contaminants, GC-MS analysis also revealed the presence of aliphatic hydrocarbons, both linear and branched, mainly in the C2–C12 range. The semi-quantitative concentration of 3-methylundecane, reported in Table 3, is representative of this fraction. These compounds may partially originate from natural sources, including degradation of organic matter. Similarly, the detection of 1,3:2,4-di-O-benzylideneribitol may be linked to plant-derived materials, as it has been previously identified in stinging nettles used in traditional medicine [54,55]. However, the absence of characteristic biomarkers such as lignin derivatives or long-chain plant waxes suggests that natural organic matter plays a limited role in the overall composition.

Table 3. Semi-quantitative estimated concentration of the compounds detected in more than one extraction solvent and related to soil pollution.

Compound	Estimated Concentration [ng/mg]	WHO 2013 [a]
2,4-Dimethylhept-1-ene	0.31	n.d.
Diethyl phthalate	0.10	13733 *
Hexan-2-one	0.07	n.d.
3-Methylundecane	0.06	n.d.
Methyl 2-(1,1-dimethylethyl)-2-methylpropanoate	0.09	n.d.
Styrene	0.07	0.68

[a] WHO guidelines [33]; * related to the total amount of phthalates.

In contrast, the presence of middle-chain methyl esters (C7–C10), commonly used as fragrance components in detergents and personal care products, points toward anthropogenic inputs and may contribute to the characteristic odor of the samples [56].

Overall, the organic fraction is dominated by compounds that are more consistent with anthropogenic contamination than with natural soil organic matter. These findings suggest that wastewater dispersion, improper waste management, and plastic degradation may represent possible pathways contributing to the detected organic compounds. This interpretation is supported by the growing body of literature reporting the presence of microplastics and related compounds in soils and sediments, although data for African regions remain limited [57]. Studies conducted in Tanzania identified polyethylene and polypropylene as dominant plastic residues in agricultural soils [14], while microplastics have also been detected in table salts across several African countries [58].

At the same time, investigations in East Africa have largely focused on emerging contaminants in aquatic systems, such as pharmaceuticals and pesticides [59], which were not observed in the present samples. This discrepancy highlights the relevance of local factors, particularly poorly managed solid waste and wastewater, as primary drivers of soil contamination in the studied area. The widespread use and improper disposal of plastic materials, especially in rapidly urbanizing or economically constrained regions, contribute significantly to environmental pollution and associated health risks [60,61].

In Somalia, the lack of structured waste management systems exacerbates these issues. Field observations and surveys conducted in Mogadishu have documented extensive plastic pollution, particularly from single-use bags [62], and a gap between environmental awareness and effective waste management practices [63]. Although regulatory measures such as bans on single-use plastics have been introduced in several countries of the Horn of Africa, their implementation and effectiveness remain uncertain [64]. While the present study does not directly assess humanitarian or public health conditions, the local environmental context provides an important framework for interpreting the analytical findings. Inadequate waste management, limited sanitation infrastructure, and water scarcity may contribute to the introduction, accumulation, and persistence of the organic compounds detected in the investigated surface materials. In and around El-Bur, prolonged conflict, population displacement, and recurrent drought have severely limited access to safe water, sanitation, and waste management services. These conditions increase the risk of waterborne diseases, as evidenced by recent cholera outbreaks [65], and contribute to the accumulation and persistence of environmental pollutants. Similar situations have been reported in other regions affected by humanitarian crises, where poor sanitation and overcrowding exacerbate health risks [4,66].

The presence of trace organic compounds in the analyzed material, even at low concentrations, therefore, represents a relevant environmental and public health concern. The lack of systematic data on soil contamination in Sub-Saharan Africa further emphasizes the importance of this study as a preliminary assessment [9,67]. Addressing these challenges requires integrated WASH (Water, Sanitation and Hygiene) interventions, improved waste management strategies, and context-specific remediation approaches.

Encouragingly, community-based initiatives implemented in other Somali regions have demonstrated that improvements in waste collection, recycling, and organic waste valorization can generate both environmental and socio-economic benefits [68]. However, the extension of such interventions to El-Bur remains challenging due to ongoing security issues and population instability [69], which continue to limit the feasibility of large-scale policy implementation.

4. Conclusions

This study provides an integrated multi-technique characterization of soil samples collected in El-Bur, central Somalia, a region affected by prolonged drought and limited environmental monitoring data. The combined use of XRD, SEM-EDX, ICP-OES, and GC-MS allowed the identification of both inorganic and organic components, offering an integrated view of the investigated surface materials. The main novelty of this work lies in providing the first integrated mineralogical, elemental, and organic characterization of surface materials from El-Bur, an area for which systematic environmental information is currently very limited. This approach provides an initial baseline for evaluating the coexistence of natural salinization processes and potential anthropogenic contamination signatures in an underexplored region. The analyzed material is predominantly composed of halite, as confirmed by crystallographic, morphological, and elemental analyses, indicating strong salinization processes. The occurrence of halite-rich aggregates in the upper soil layer suggests surface salt accumulation driven by evaporation and upward migration of saline groundwater, consistent with the hydrogeochemical conditions reported for the region [20,24,36].

In parallel, GC-MS analysis revealed the presence of trace organic compounds, including plastic-related molecules such as styrene, diethyl phthalate, and aliphatic hydrocarbons. Although their concentration remains below guideline thresholds [33], their distribution across multiple extraction solvents suggests contributions from external sources, likely associated with plastic waste, wastewater dispersion, and combustion-related emissions.

Overall, the results highlight a combined influence of natural and anthropogenic factors. Natural drivers, including arid climate and saline groundwater, appear to dominate the inorganic composition, while localized human activities contribute to the presence of organic contaminants. The absence of typical soil organic matter biomarkers further indicates a system characterized by low organic content and limited biological activity.

Although the limited number of samples prevents a statistically representative assessment at the regional scale, the consistency among independent analytical techniques supports the reliability of the observed trends within the investigated materials. In this context, the present study should be considered as an initial environmental assessment that provides a first integrated baseline for an underexplored area where systematic environmental data are scarce. Beyond supporting future research activities, such information may contribute to the identification of environmental priorities and to the development

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of context-specific soil and water management strategies [9]. However, the observations reported here should be interpreted as applicable only to the investigated materials and not as a comprehensive assessment of soil quality or contamination status at the regional scale.

Some limitations should therefore be acknowledged. The limited number of samples analyzed, selected from specific locations within the urban area of El-Bur, does not allow statistical extrapolation to the entire region. Moreover, the exploratory nature of the study and the absence of long-term monitoring data limit the possibility of establishing temporal trends or fully identifying contamination sources. Nevertheless, the consistency observed among independent analytical techniques supports the reliability of the identified patterns and provides a basis for future investigations and environmental management actions in a region where environmental data remain scarce. Further studies involving extended spatial sampling, depth profiling, and seasonal monitoring are necessary to better understand the variability of soil composition, identify contamination sources, and support the development of sustainable soil and water management strategies in arid and resource-limited environments.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app16157611/s1: Figure S1: Appearance of the Somali soil samples at the time of collection.

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