Review

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Review

Earth Observation in the EMMENA Region: Current Applications and Knowledge Gaps

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Abstract: Earth Observation (EO) techniques have significantly evolved over time, covering a wide range of applications in different domains. The scope of this study is to review the research conducted on EO in the Eastern Mediterranean, Middle East, and North Africa (EMMENA) region and to identify the main knowledge gaps. We searched through the Web of Science database for papers published between 2018 and 2022 for EO studies in the EMMENA. We categorized the papers in the following thematic areas: Atmosphere, Water, Agriculture, Land, Disaster Risk Reduction (DRR), Cultural Heritage, Energy, Marine Safety and Security (MSS) and Big Earth Data (BED); 6647 papers were found with the highest number of publications in the thematic areas of BED (27%) and Land (22%). Most of the EMMENA countries are surrounded by sea, yet there was a very small number of studies on MSS (0.9% of total number of papers). This study detected a gap in fundamental research in the BED thematic area. Other future needs identified by this study are the limited availability of very high resolution and near real time remote sensing data, the lack of harmonized methodologies and the need for further development of models, algorithms, early warning systems and services.

Keywords: Eastern Mediterranean, Middle East, and North Africa (EMMENA) region; atmosphere; water; agriculture; land; disaster risk reduction; cultural heritage; energy; marine safety and security; big earth data

1. Introduction

Earth observation (EO) via remote sensing technologies provide information about our planet's physical, chemical and biological systems [1]. This type of information is crucial in regions which are exposed in various risks (e.g. climate change, droughts, floods, earthquakes and landslides), and where ground data are scarce [2–5], such as the Eastern Mediterranean, Middle East, and North Africa (EMMENA) region [6].

We define as EMMENA the geographical region which includes the following countries: Algeria, Bahrain, Cyprus, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Malta, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Syria, Tunisia, Turkey, United Arab Emirates and Yemen. The EMMENA region hosts approximately 558 million people, covers an area of 12046012 km^2 and it is one of the most diverse regions in the world in economic terms, with per capita annual gross domestic products (GDP) ranging from US$ 533 in Yemen to US$ 66838 in Qatar [7]. The region has a rich history and cultural heritage but has also been exposed to various risks over the decades. EMMENA region has been suffering by geopolitical tensions, political instability, and conflicts [8]. Furthermore, population growth and expanding urbanization in EMMENA region have increased the pressure on ecosystems and on available resources [9–12]. In addition, this region has been characterized as a

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Climate change hot spot, leading to increasing temperatures, extended droughts and decline in rainfall [13,14]. The agricultural sector, of which 70 percent is rainfed, is highly exposed to changing climatic conditions [14]. This is of critical importance as the agriculture sector contributes significantly to the national economies of many EMMENA countries. Additionally, Climate change will have negative impacts on many other aspects including air quality, human health, land ecosystems, marine ecosystems, freshwater resources and on energy demand [15,16]. Finally, many countries of the EMMENA region are situated on complex topography and on tectonically active areas, thus are prone to hazards related to landslides and earthquakes [17].

EO plays a crucial role in understanding processes on our planet, enabling us to advance our monitoring capabilities over various domains of interest [18]. The information generated from EO enables researchers and decision-makers to formulate and apply effective policies for environmental protection and sustainable management of natural resources. The amount of freely accessible EO data has been increasing over the years, mainly due to technological advancements and the implementation of open data policies. For example, the yearly volume of open and freely available satellite data increased from 0.25 PB in 2013 (MODIS and Landsat missions) to 4.25 PB in 2019 (MODIS, Landsat and Sentinel missions) [19]. These data provide the opportunity to expand our knowledge in many thematic areas including atmosphere, water, agriculture, land, disaster risk (reduction), cultural heritage, energy and marine safety and security. However, due to the expanding amount of data, there is a need for novel solutions to properly store, process, disseminate and analyze these big earth data sets [18].

The on-going development of Big Earth Data techniques and the increasing availability of satellite EO data provide opportunities to better monitor the aforementioned thematic areas [20,21]. As the EMMENA region is a fairly new segment for EO activities [6], it is crucial to document the current EO applications per thematic area and to identify the existing knowledge gaps, as this will provide opportunities for the EMMENA countries to establish collaborations and to strengthen and expand in the field of EO. Thus, the main objective of this study is to review the research conducted on EO in the EMMENA region per country and per thematic area and to identify the main knowledge gaps for the past five years.

2. Materials and Methods

The key word searches were conducted in the Web of Science ™ database to find articles about EO in the EMMENA region for the past five years. As search terms, we selected the "Topic" option which searched journals' title, abstract and keywords for the following keywords: "Remote sensing OR Satellite OR Earth observations OR GIS OR geographical information systems". With the ''AND Topic" option, we constrained the research only for the EMMENA region by inserting the following keywords: "Algeria OR Bahrain OR Cyprus OR Egypt OR Iran OR Iraq OR Israel OR Jordan OR Kuwait OR Lebanon OR Libya OR Malta OR Morocco OR Oman OR Palestine OR Qatar OR Saudi Arabia OR Syria OR Tunisia OR Turkey OR United Arab Emirates OR Yemen". Additionally, with the "AND Year published" option we further constrained the search for the past five years by inserting the following: "2018-2022". Articles not written in English language and not having a digital object identifier (DOI) were excluded from the analysis. Articles of which their study area covered more than one country were named as "regional". Author names and affiliations, the journal title, keywords and abstracts, the number of citations and the DOI were exported and analyzed in EXCEL® (MICROSOFT, USA) and in ArcGIS Pro (ESRI, USA).

The papers were also categorized in the following thematic areas based on the relevant EO applications (Table 1): Atmosphere (ATM), Water (WAT), Agriculture (AGR), Land (LAN), Disaster Risk Reduction (DRR), Cultural Heritage (CH), Energy (EN), Marine Safety and Security (MSS) and Big Earth Data (BED). The latter thematic area which includes Data Mining and Information Extraction, Machine Learning and Artificial Intelligence, Visual Exploration and Semantic Enrichment, Geo-information, can be also consider as a horizontal thematic area as its applications are often supplementary to the rest of the thematic areas. Articles which were not classified in any of the above thematic areas were named as "other" and articles which were classified in more than one thematic area were named as "interdisciplinary". Thus, some articles were categorized in more than one thematic area. The top 10 cited articles (up to 13 March 2023) from each thematic area were further examined to identify current EO applications and knowledge gaps.

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The analysis included the citation topics at the micro-level, which were downloaded from Web of Science ™. The citation topics at micro-level include 2437 topics which are algorithmically derived with the use of an algorithm developed by CWTS, Leiden [22]. Also, the analysis included the top 10 affiliations and the top 25 authors with the highest number of publications and their affiliations. Finally, data for the population, area and Gross Domestic Product (GDP) of each country within the EMMENA region were available from The World Bank [7] and the International Monetary Fund [23] (Table 2).

Table 1. Indicative EO Applications per thematic area.

Thematic area	Indicative EO Applications
Atmosphere	Air Quality/Air pollution Aerosol Clouds Precipitation Atmospheric Dynamics/ Wind Atmospheric Events Dust storms/ Dust intrusion Climate change Atmospheric/Climate models
Water	Hydrological monitoring Water quality monitoring Water resource management (Water) Microbial risk assessment Water leak detection Managed aquifer recharge Hydrological - Hydrogeological modeling Water policies Water diplomacy
Agriculture	Precision Agriculture Irrigation scheduling Agricultural Policies Soil health Pest/disease control Food security / Food safety Early warning systems Damage assessment and mitigation strategies for extreme weather events
Land	Land Cover/ Land Use changes Forest dynamics Urban sprawl monitoring Real Estate Heat island Spatial planning Urban and regional planning Land Management Information systems DEM generation Photogrammetric applications
Disaster Risk Reduction	Forest fire monitoring Burnt area mapping Systematic monitoring of geohazards Soil erosion detection Soil degradation/desertification

	Floods monitoring Epidemics/Health Impact assessment Disaster management Early Warning Systems Decision Support Systems
Cultural Heritage	Risk assessment of Cultural Heritage from natural and anthropogenic hazards Protection of Cultural Heritage Cultural Heritage digitization (3D models) Archaeo landscape assessment and modelling Study of unexcavated areas UAV photogrammetric applications
Energy	Energy potential Optimal site selection of power plants Energy Infrastructure Planning Environmental impact assessment
Marine Safety and Security	Bathymetry Land-Water line Wave groups -Wave breaking Surface currents Marine spatial planning Sea state Sea winds Ship detection Oil spills Posidonia monitoring
Big Earth Data	Data Mining and Information Extraction Machine Learning and Artificial Intelligence Visual exploration and Semantic Enrichment Geo-information.

Table 2. Population (Po), area (A), per capita Gross Domestic Product (GDP.P.C), and number of author and co-author affiliations (A.A) per country, as percentage of the total number of affiliations and author affiliations per capita (A.A.P.C) for EMMENA countries (measured in ppm).

Countries	Po	A (Km^2)	GDP.P.C ($)	A.A	% of total	A.A.P.C (in ppm)
Algeria	44616624	2381741	3691	251	2.1	56
Bahrain	1792761	760	26563	14	0.1	78
Cyprus	1207359	9251	31552	93	0.8	770
Egypt	104258327	1002450	3699	779	6.6	75
Iran	85028759	1648195	4091	2186	18.4	257
Iraq	42698349	438317	4775	207	1.7	48
Israel	9389000	20770	52170	168	1.4	179
Jordan	10824649	89342	4103	129	1.1	119
Kuwait	4270571	17818	24300	65	0.5	152
Lebanon	6825445	10452	4136	57	0.5	84
Libya	6871292	1759540	6357	19	0.2	28
Malta	502650	316	33487	23	0.2	458
Morocco	38995602	446550	3795	372	3.1	95
Oman	5106626	309500	19509	181	1.5	354

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Palestine	5337000	6020	2848	31	0.3	58
Qatar	2832067	11586	66838	48	0.4	169
Saudi Arabia	35340683	2149690	23185	544	4.6	154
Syria	17505228	185180	533	22	0.2	13
Tunisia	11818619	163610	3807	219	1.8	185
Turkey	83614362	783356	9661	1010	8.5	121
United Arab Emirates	9599353	83600	44315	126	1.1	131
Yemen	29161922	527968	702	20	0.2	7
Other Countries	-	-	-	5320	44.8	-
Total	557597248	12046012		11884	100.0	

3. Results and Discussion

3.1. Number of EO Studies in the EMMENA Region

The total number of publications in EO applications in the EMMENA region from 2018 to 2022 was 6647 (Figure 1); 1291 of these studies had a regional geographic focus, extending beyond country borders. The geographic focus of most publications was on Iran (1883 publications), while EO studies in Bahrain were the least (10 publications). Similarly, for the author affiliation country (Table 2), Iran has the highest (2186) and Bahrain has the lowest (14) number of affiliations. However, 44.8% of the authors' affiliations are not within the EMMENA region. Considering the population of each country, Cyprus has the highest author affiliation per capita (770 per 1 million people). Countries that are suffering from political and military conflicts, such as Libya and Yemen, have the lowest author affiliation per capita (7 and 13, respectively). This is also mirrored in the low per capita GDP of these countries (Table 2).

The list with the 6647 publications including author name, article title, author keywords and addresses, citations and DOI is presented in the supplementary material (Table S1).

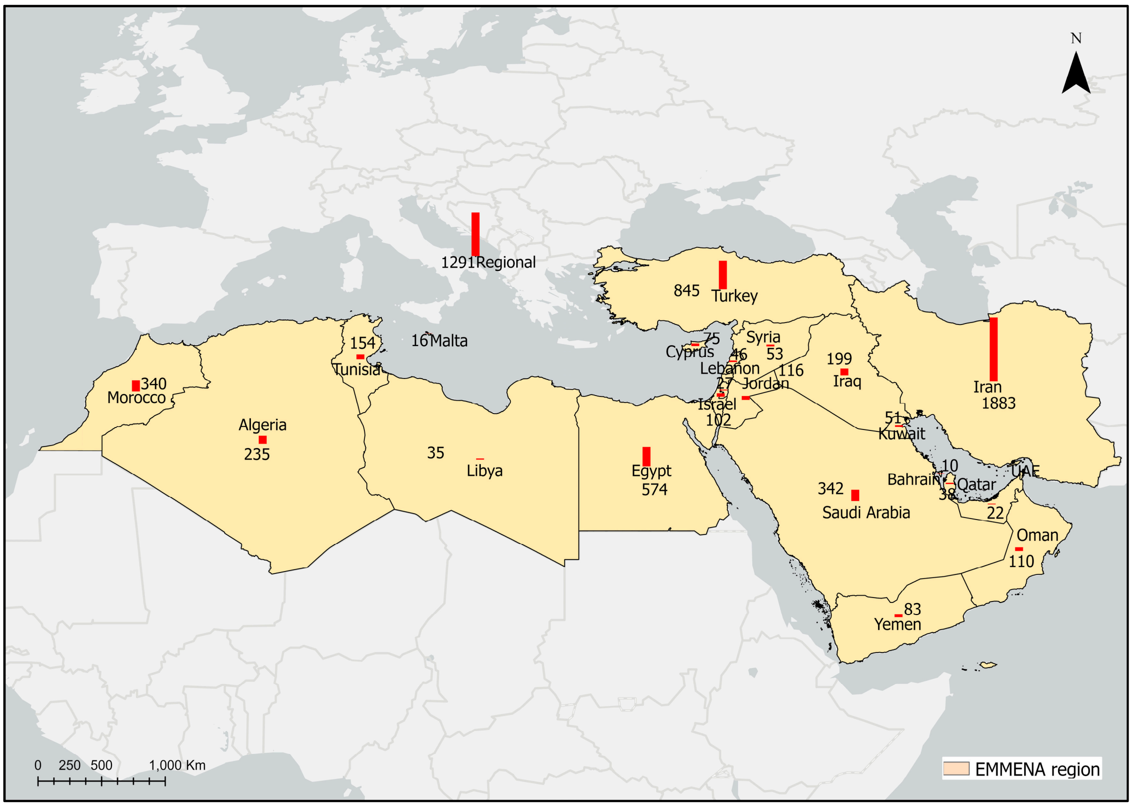

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Figure 1. Number of publications (red column) per country in the EMMENA region

3.2. Authors with the Highest Number of Publications Focusing in the EMMENA Region

The 10 institutions with the highest number of affiliations (authors and co-authors) as identified in the EO publications in the EMMENA region are the following: University of Tehran (416 records), Islamic Azad University (346 records), Tarbiat Modares University (196 records), National Authority for Remote Sensing Sciences – NARSS (173 records), Shiraz University (167 records), Centre National de la Recherche Scientifique – CNRS (166 records), university of Tabriz (157 records), King Abdulaziz University (149 records), Istanbul Technical University (137 records) and Khajeh Nasir Toosi University of Technology (122 records). Six out of ten of these institutions are in Iran.

The 25 authors with the highest number of publications focusing in the EMMENA region are shown in Figure 2. Twelve of these authors have affiliation in countries not included in the EMMENA region (Australia, Austria, Canada, Finland, Germany, Malaysia, Norway, South Korea, Spain, Sweden, Taiwan and USA). Ten authors have affiliations in Iran (Shiraz University, University of Kurdistan, Tarbiat Modares University, Agricultural Research, Education and Extension Organization, University of Tabriz, Isfahan University of Technology and Shahid Rajaee Teacher Training University). The remaining 3 authors are affiliated in Morocco (Mohammed VI Polytechnic University), Cyprus (Cyprus University of Technology) and Saudi Arabia (King Abdul Aziz University).

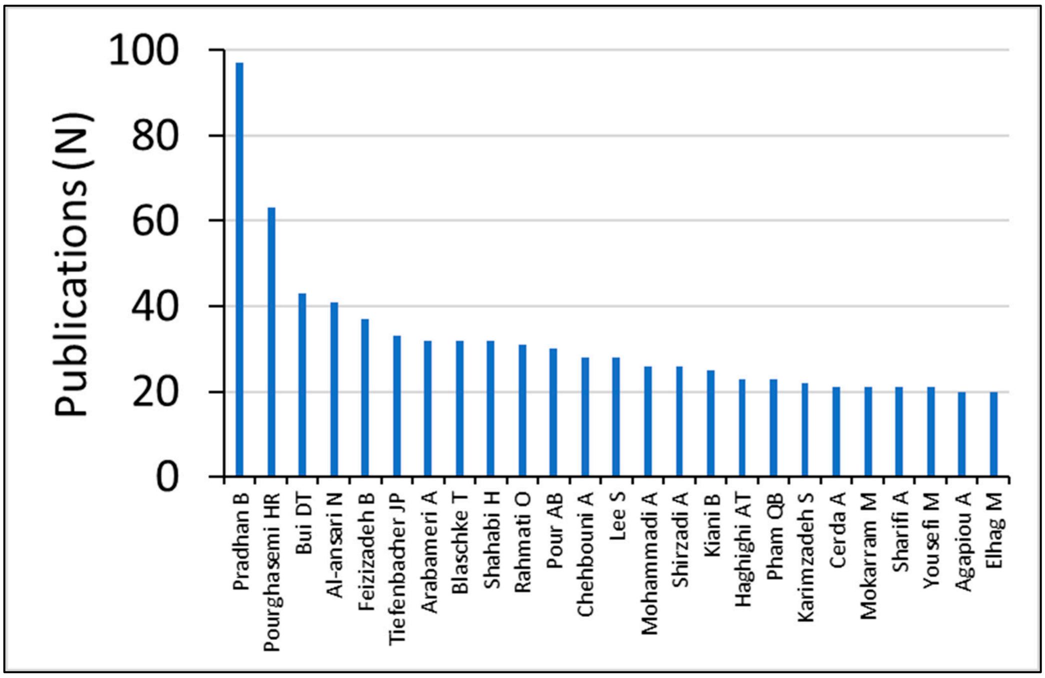

Figure 2. Top 25 authors with highest number of publications for papers on EO at the EMMENA region.

3.3. EO Research per Country and per Thematic Area in the EMMENA Region

Big Earth Data is the thematic area with the highest contribution (27.1 %) of EO research done in the EMMENA region (Figure 3). Surprisingly, while most of the EMMENA region countries are surrounded by sea, Marine Safety and Security has the lowest contribution of EO research done in the EMMENA (0.9%). Also, EMMENA region is characterized by long history and Cultural richness [8], but EO applications on Cultural Heritage have a low contribution to the total number of studies (1.4%).

A total of 495 citation topics were identified in Web of Science, of which the first 10 account for 46% of the total number of publications. These topics include Normalized Difference Vegetation Index (NDVI) (9%), groundwater (6%), evapotranspiration (6%), landslides (6%), fuzzy sets (4%), ecosystem services (4%), Aerosols (3%), Geostatistics (3%), soil erosion (3%) and tectonics (2%).

Most publications for EO applications in the EMMENA region used Landsat and Sentinel data, as identified by the keyword search on the publications' title, keywords and abstract (Table 2).

Sentinel-2 data (60.8%) and Sentinel-1 data (35.4%) are the most widely used among the Sentinel missions. Similarly, Landsat 8 (83.2%) and Landsat 7 (10.0%) are the most widely used data sources among the Landsat missions.

The detailed analysis of the EO research done according to the top ten highly cited articles per thematic area will be described in the following subsections.

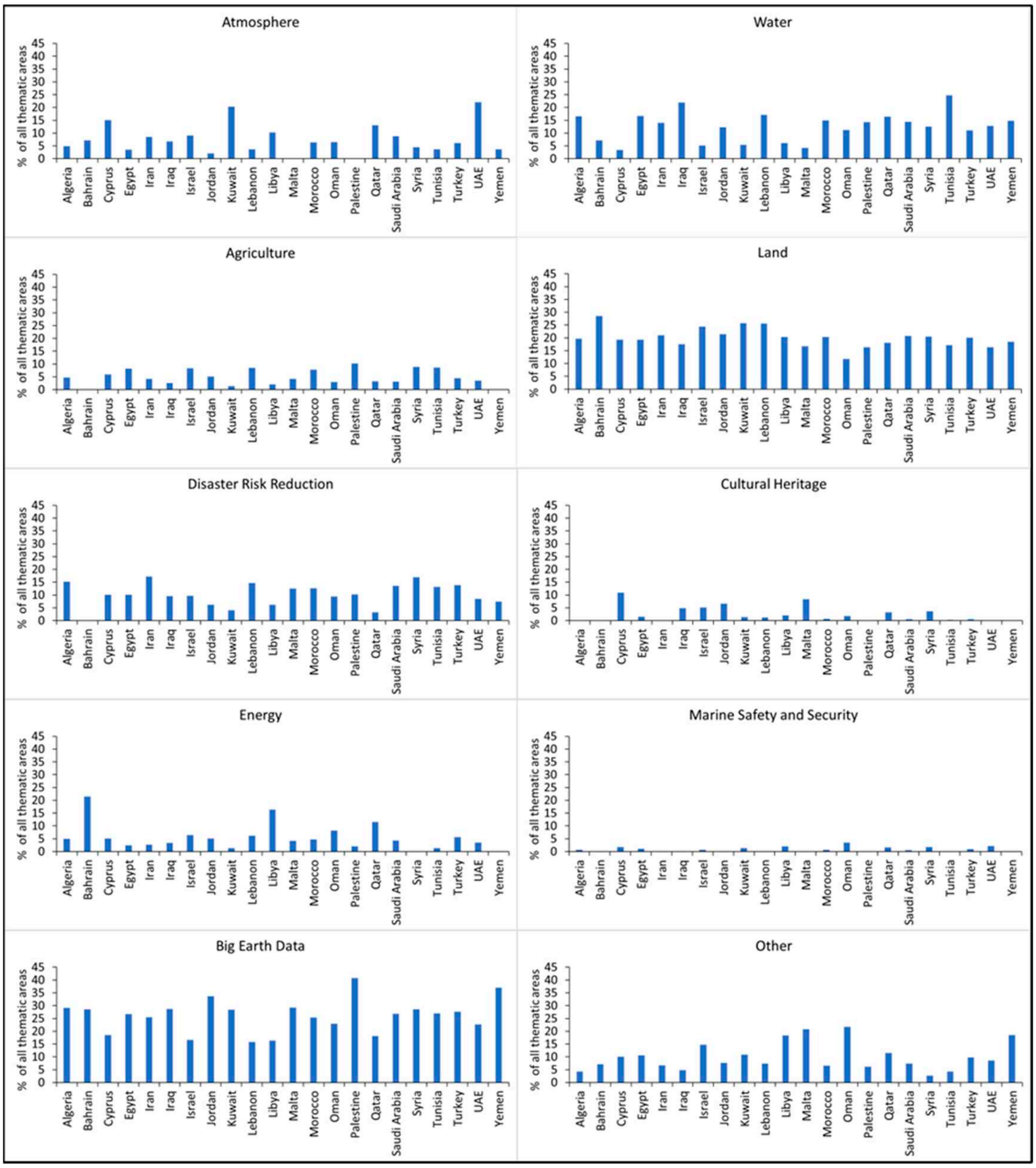

Figure 3. EO applications per country and per thematic area (% of all clusters).

Table 2. Percentages of satellite missions per appearance in the title, keywords and abstract of EMMENA publications.

Satellite mission	Title	Keywords	Abstract
Landsat	24.6	28.2	29.8
Sentinel	30.2	25.9	22.6
MODIS	12.6	17.5	14.1
ASTER	9.1	7.9	6.5

GRACE	3.3	3.9	3.4
TRMM	2.4	2.6	4.1
SPOT	1.7	1.2	1.3
WorldView	1.5	1.4	1.4
PlanetScope	1.5	0.7	0.6
Other	12.9	10.7	16.2

3.3.1. Atmosphere

Four out of the 10 highest cited articles in the thematic area of atmosphere focused on the impact of Coronavirus on air quality through EO. Spaceborne NO_2 column observations from two high-resolution instruments, Tropospheric Monitoring Instrument (TROPOMI, Sentinel-5 Precursor) and Ozone Monitoring Instrument (OMI), were used to assess the impact of COVID-19 outbreak on NO_2 pollution on five different regions (China, South Korea, western Europe, USA and Iran) [24]. The results showed 20-40% decrease in NO_2 columns over China, Europe, South Korea, and the United Sates between January and April 2020, due to the lock-down measures implemented by the governments. A likely explanation for the absence of NO_2 decrease in Iran is that complete lockdowns were not enforced in Iran. The authors emphasized that further studies are needed to evaluate the effects of the temporary lockdowns on global air quality and climate, and the gradual return to pre lockdown periods. On the contrary, the study of Broomandi et al. [25] showed that the COVID-19 lockdown positively affected Iran's air quality, as evident by the reduction in the levels of CO, NO_2, SO_2, and PM_{10}. Similar trends of NO_2 reduction during the lockdown were observed for other EMMENA countries, such as Egypt and Iraq [26,27].

The remaining studies on the Atmosphere thematic area focus on precipitation estimates [28,29], improvement of CO2 anthropogenic emission measurements [30], climate change [31,32] and dust storms[33].

Reuter et al. [30] developed a co-location method with the simultaneous use of CO_2 (OCO-2) and NO_2 (Sentinel-5) data for the identification and quantification of anthropogenic emission plume signals. The authors highlighted that existing satellites present high flux uncertainties which are expected to be reduced by the planned European Copernicus anthropogenic CO_2 monitoring mission (CO2M), due to higher spatial resolution and better imaging capabilities.

The two articles which focus on the improvement of precipitation estimates used a combination of modelling applications, multiple data sources (European Centre for Medium-Range Weather Forecasts-ECMWF, Tropical Precipitation Measuring Mission-TRMM), and improved algorithms [28,29].- These studies underlined that future studies should account for uncertainties related to the spatial variability, over regions with complex topography.

The study of Namdari et al. [33] examined the impacts of climate fluctuations on dust storm activity over the Middle East. They used Aerosol Optical Depth, temperature, and precipitation data between 2000 and 2015, obtained from MODIS Collection, Tropical Rainfall Measuring Mission (TRMM; https://pmm.nasa.gov/index.php), Global Historical Climate Network (GHCN; http://www.esrl.noaa.gov/psd/data/gridded/data.ghcncams.html) of the NCDC/NOAA , ECMWF (http://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=sfc) and from the Iran Meteorological Organization (IMO). Their results indicate that long-term reduction in rainfall has promoted lower soil moisture and vegetative cover, leading to more intense dust emissions. Furthermore, short term variations in temperature in hot periods exacerbate the influence on the dust storm genesis.

Long-term trends between vegetation and climate showed apparent Climate change effects in Iran [31]. Using 33-year records of NDVI (calculated with data from the Advanced Very High Resolution Radiometer (AVHRR) satellite) and climate variables Lamchin et al. [31] found that the vegetation greenness trend consistently decreased (range=−0.47 to−0.08) in eastern Iran. Similarly, projected Land Use Changes for Saudi Arabia between 2014 and 2100 showed reductions in vegetation due to climate change and anthropogenic activities [32].

3.3.2. Water

The top 10 highly cited articles in the water thematic area focused on mapping groundwater potential and groundwater quality [34–43]. According to Arabameri et al. [43], due to the constant technical advancements in the field of groundwater potential mapping, there is no current agreement or reference on which approach is more suitable to predict high groundwater potential. However, all studies have in common the use of GIS software and geostatistical methods, including different models and algorithms. The studies used various sources of data (e.g., ALOS PALSAR, ASTER, Landsat, ground-based) related to water quantity and quality, land use/ land cover, soil and geology, digital elevation, morphological (e.g., slope, aspect) and hydrological data (e.g., river network). The choice of the input data depends on the site-specific characteristics of each region. All these studies highlighted that the results will be useful for better water and land management practices and policies.

3.3.3. Agriculture

The EO applications in the thematic area of Agriculture covers a wide range of topics such as evapotranspiration (ET) estimation [44,45], land suitability for agriculture [46–49], irrigation mapping [50], agricultural land loss [51] and crop monitoring [52,53]. The studies on evapotranspiration were conducted with ET models based on MODIS and Landsat satellite data, in Iran. The authors emphasized the need for high quality in situ data in future studies, to improve the model's performance. Land suitability studies were conducted both with GIS and multi-criteria decision-making analysis for maize (Iran), soybean (Iran), rapeseed (Iran), barley (Iran) and jojoba (UAE) crops. The studies reported that their findings can help in improving the management of crop production and that future studies should expand on different crops and soil types.

In their study on soil moisture and irrigation mapping in Tunisia, Bousbih et al [50] presented a new technique based on the synergistic interpretation of multi-temporal optical and Synthetic Aperture Radar (SAR) data (Sentinel-2 and Sentinel-1). Their approach is based on the inversion of the Water Cloud Model, using radar data and NDVI data derived from optical images. Their results showed an RMSE of 4.3% and a bias of 1.9% between the satellite and observed data.

Crop growth dynamic observations from satellites are often limited by the coarse spatial and temporal resolutions. To address this issue Nguyen et al.[53] proposed the use of data from different ongoing satellite missions Sentinel-2 (ESA) and Landsat 7/8 (NASA) through harmonization techniques. They found that improved topographic correction models are needed to achieve higher performance of the harmonized products in mountainous areas. Sadeh et al. [52] developed a new method to fuse a time series of images sourced from two different satellite constellations (Sentinel-2, Planetscope) which combines the advantages of each satellite (high temporal, spatial and spectral resolution). This new technique was applied to create spectrally consistent daily images of wheat LAI at a 3 m resolution which were then compared with in-situ wheat LAI measurements from Australia and Israel. Their approach successfully estimated LAI ($R^2 = 0.94$) throughout the growing season for LAI < 3.

Urban expansion has critical consequences for agricultural production in the EMMENA region. Radwan et al. [51] analyzed 24 LULC maps from the European Space Agency-Climate Change Initiative (ESA-CCI) land cover viewer (http://maps. elie.ucl.ac.be/CCI/viewer/) and found that 74,600 hectares of fertile agricultural land in the Nile Delta (Old Lands) was lost due to urban expansion from 1992 to 2015 at an average rate of 3108 ha year^{-1}. Also, 206,100 hectares of bare land was converted to agricultural land at an average rate of 8588 ha year^{-1}. According to the authors, more sustainable land-use strategies are needed to minimize the threats to agricultural sustainability and food security.

3.3.4. Land

Most of the studies in land thematic areas focus on erosion processes [54–59] where various satellite data (e.g. ALOS-PALSAR, Landsat, ASTER G-DEM, Sentinel) ground data, statistical approaches and GIS techniques are applied to create erosion susceptibility maps. However, the selection of data, approaches and techniques depends on the data availability and the site-specific characteristics of each study. All these studies reported high accuracy of the maps and that their results will help towards better land use planning and risk management.

The remaining four studies focused on land use/land cover (LULC) monitoring [60,61], forest biomass estimation [62] and on soil properties mapping [63]. Mansour et al. [61] applied advanced

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GIS techniques, spatial modelling and utilization of satellite images (Landsat 5/8) to simulate LULC changes and to predict the urban expansion in the mountainous cities of Oman, for the years 2028 and 2038. Their predictions showed 50% increase in the built-up area in 2038; on the contrary, vegetation will decrease by 36.5%. Ghorbanian et al. [60] developed an object-based land cover classification methodology using the Google Earth Engine in order to improve the land cover map of Iran. They used Sentinel-1 and Sentinel-2 imagery data for the fusion of SAR and multi-spectral data to increase the land cover classification accuracy. The land cover map for Iran (2017) had an overall accuracy of 95.6%.

Zeraatpisheh et al. [63] used the Normalized Difference Vegetation Index (NDVI), Ratio Vegetation Index (RVI), Perpendicular Vegetation Index (PVI), Clay Index (CI), Landsat image band 4 (B4) and Soil Adjusted Vegetation Index (SAVI), derived from the Landsat enhanced thematic mapper, in order to predict and compare the spatial distribution of soil organic carbon (SOC), calcium carbonate equivalent (CCE) and clay content by using different machine learning techniques (Cubist, Random Forest , Regression Tree and a Multiple Linear Regression) in Iran. Their results showed that the highest and the lowest prediction accuracies were obtained for clay and SOC using Random Forest and Random Tree models, respectively. Similarly, machine learning techniques were applied by Vafaei et al. [62] in order to improve the forest above ground biomass estimation. They generated three datasets including the Sentinel-2A dataset, the ALOS-2 PALSAR-2 dataset, and the combination of the Sentinel-2A dataset and the ALOS-2 PALSAR-2 dataset (Sentinel-ALOS). They found that above ground biomass models derived from the combination of the Sentinel-2A and the ALOS-2 PALSAR-2 data had the highest accuracy, followed by models using the Sentinel-2A dataset and the ALOS-2 PALSAR-2 dataset.

3.3.5. Disaster Risk Reduction

Disaster risk reduction is the thematic area with the highest average number of citations per thematic area for the top 10 cited papers (Figure 4). The focus of these papers is on landslides [64–69] and on floods [70–73]. All these papers have in common the use of Machine learning, Artificial Neural Networks or both techniques.

According to Merghadi et al. [65] tree-based ensemble algorithms achieve excellent results compared to other machine learning algorithms for landslide susceptibility mapping. Specifically, the Random Forest algorithm offers robust performance for accurate landslide susceptibility mapping with only a small number of adjustments required before training the model. Pourghasemi and Rahmadi [69] reported similar results for the Random Forest algorithm on their review study on landslide susceptibility. According to Reichenbach et al. [64] for the preparation of landslide susceptibility assessment there are 9 steps that need to be considered, which include obtaining relevant landslide and thematic information, selecting appropriate mapping unit and model, evaluating model fitting and predictive performance, estimating model uncertainty and ranking model quality and designing the landslide protocol. Future studies should consider these steps and focus on the development of landslide early warning systems at different geographical scales.

Remote sensing data on land cover, morphology and hydrology are essential both for landslide and flood research. According to Ahmadlou et al. [70], flood occurrence is mainly affected by plan curvature, followed by altitude, geology, distance to river, slope and soil, land use, rainfall and slope aspect. A range of models and machine learning techniques have been applied in order to improve the flood susceptibility mapping [72,73]. However, future studies should focus on the development of flood forecasting and warning systems which is essential in order to minimize the flood hazards [71].

3.3.6. Cultural Heritage

EO on Culture Heritage thematic includes detection, monitoring and management of archaeological sites [74–77], looting detection [78,79], mapping and reconstruction [80–82] and environmental risk monitoring [83].

The studies on the detection, monitoring and management employed various satellite data (Corona, Landsat, Spot, Quickbird, and Sentinel-2A, COSMO-SkyMed) and reported that there is a need for further development of machine and deep learning techniques in order to automate feature extraction and pattern detection in very high resolution (VHR) images [74,76]. Also, the combined use of LiDAR, aerial photographs, historical records and satellite images will further enhance the investigation of ancient sites [80]. By screening long Sentinel-2 time series for Aleppo and Apamea, Tapete and Cigna [74] showed that changes of textural properties and surface reflectance can be associated to events relevant for conservation. Tapete and Cigna [75] also suggested the use of COSMO-SkyMed data for condition assessment of archaeological heritage and landscape disturbance due to its capabilities for very high spatial resolution images and for site revisit of up to one day. Stott et al. [82] applied airborne laser scanning (ALS) remote sensing and photogrammetric techniques, including enhancing local topographic contrast for archaeological interpretation, residual relief modelling, sky view factor, and local dominance, and they were able to accurately map known archaeological features and to detect a wide variety of previously unrecorded potential features. A major issue for the preservation of archaeological areas appears to be urban and agriculture sprawling [74,77,82,83].

Lasaponara and Masini [79] introduced an automatic method for archaeological looting feature extraction approach (ALFEA) which is based on the looting enhancement using spatial autocorrelation, unsupervised classification, and segmentation. For their analysis they used images available from Google Earth. Their results from the evaluation procedure showed satisfactory performance from two analysed test cases with a rate of success higher than 90%. According to the review study by Tapete and Cigna [78], a variety of satellite data were used for the detection of archaeological looting, such as HR multispectral imagery from Sentinel-2, VHR X-band SAR data from the COSMO-SkyMed, VHR panchromatic and multispectral WorldView-2 imagery and VHR optical data from GeoEye-1, IKONOS-2, QuickBird-2, and WorldView-3; 89% of the studies on looting detection exploited optical images and the majority of these studies used VHR images (less than 1 m resolution). According to the authors, the use of open high resolution (HR) data (e.g., Sentinel-2 and Landsat) is still at the early stage. Currently, there is lack of common practices in the domain of looting detection from space, thus there is a need to move toward sharing and harmonization of methodologies.

3.3.7. Energy

The top 10 highly cited articles in the Energy thematic area focus on the spatial assessment of the energy potential and on the location selection for energy plants [84–93]. Seven of these studies focus on solar energy (Photovoltaics, Concentrating Solar Power), two focus on offshore wind energy potential and one study focuses on bioethanol.

In their study on the spatial assessment of solar energy potential at global scale, Pravalie et al. [91], analyzed the solar radiation distribution and intensity based on global horizontal irradiation (GHI) and direct normal irradiation (DNI) data. They found that most of the countries located in the EMMENA region (Saharan countries and countries located in the Arabian Peninsula) present superb (maximum) solar potential, thus there are opportunities for developing solar energy at national or international (regional) level. However, there are additional factors that can affect solar power generation in this region, such as dust particles and dust storms, high air temperatures, insufficient financial resources and political instability or war conflicts.

The remaining studies have in common the combined use of GIS and Analytical Hierarchical Process Methods, except the study of Firozjaei et al. [93] in which they employed Ordered Weighted Averaging analysis for the solar energy evaluation in Iran. The assessment of the energy potential and the location of energy plants includes a range of criteria such as climatic (e.g. solar radiation, sunshine, land surface temperature), morphological (e.g. slope and aspect), locational (e.g. distance from cities, roads and electricity grid), land cover and hydrological (e.g. distance from dams and groundwater) [84–87,92,93]. The criteria for the assessment of the offshore wind energy potential include among others wind characteristics, water depth, soil substrate and distance from the shoreline, military areas, parks, submerged cables, shipping routes and fishing areas [89,90]. Finally, the criteria for Bioethanol facility location selection include social (e.g. policies, work force, societal impact, quality of life), environmental (e.g. ecologically sensitive areas) and economic (e.g. investment, maintenance and operation costs) criteria [88].

3.3.8. Marine Safety and Security

Marine safety and security is the thematic area with the lowest average number of citations per thematic area for the top 10 cited papers (Figure 4). Studies include oil spill detection and assessment [94–99], toxicity assessment of heavy metals [100], environmental pollution of coastal zones [101],

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detection of floating plastic litter [102], characterization of natural hydrocarbon seepage [103] and relative sea-level rise and potential submersion risk [104].

Research on oil spill detection and assessment was conducted with various satellite data including Sentinel-1, Planetscope, Landsat 5 and Landsat 8. Chaturverdi et al. [97] and El-Magd et al. [99] used SAR data from Sentinel-1 satellites to detect and map oil spills in the Al Khafji area (Saudi Arabia) and in the coastal waters of Egypt. Their results demonstrated the capability of utilizing Sentinel-1 for oil spill detection and mapping. Arslan [96] analyzed Sentinel-1 data to detect an oil spill caused by a ship on 18 December 2016 off the coast of Ildır Bay (Izmir, Turkey). Furthermore, Landsat 8 data were used for validation purposes by estimating brightness temperatures to observe oil spill changes in temperature on the sea surface. Park et al. [95] combined very high resolution satellite images (Planetscope) with an Artificial Neural Network technique to detect oil spill accidents occurred on 10 August 2017 near the Ras Al Zour area (Kuwait). The accuracy and kappa coefficient of the oil classification map obtained from the optical image were 82.01 % and 72.42 %, respectively. Future studies should focus on satellite data of higher temporal resolution, to verify the results with in-situ or satellite SAR data and to develop better algorithms for rejecting low-probability pixels and dust. Finally, there is a need to develop a near-real-time warning and alarm system for oil spill cases as a service, which can help to identify the ship or platform that is liable for the pollution [99].

Ivanov et al. [103] studied the hydrocarbon seep characteristics and their relation to the local hydrocarbon field or potential hydrocarbon reservoirs in the South Caspian sea (Iran). They analyzed SAR images (Sentinel-1) together with bathymetry, geological and geophysical data with GIS. Their results showed that the oil slicks have natural origin, related to the bottom seepage phenomenon, and associated with an existing hydrocarbon system.

Fatehian et al. [101] designed and implemented an integrated Volunteered Geographic Information (VGI)-based system based on coastal pollution management concepts and public participation in order to monitor coastal pollution in Nowshahr port city (Mazandaran Province, Iran). Tourists, residents, and other present individuals were asked to report observable pollutants at their location; 86% of the reports referred to the accumulation of garbage, while 10% and 4% of the remaining reports were related to the wastewater pollution and oil contaminants, respectively. According to the authors, future work should focus on the integration of Spatial Decision Support Systems (SDSSs) in the existing tool to improve coastal pollution management.

El-Alfy et al. [100] used Landsat OLI images, synchronized with the sampling time of water and sediment samples to assess the toxicity of heavy metals and organochlorine pesticides in freshwater and marine environments in Rosetta area (Egypt). They found that drainage canals, cultivations and urbanized zones were the major sources of contamination in the studied area. They recommended biological treatment processes such as using naturally grown plants like Phragmites australis in the contaminated sites.

Themistocleous et al. [102] examined the potential of detection of the floating plastic litter by introducing the Plastic Index (PI) and Reversed Normalized Difference Vegetation Index (RNDVI), based on the Sentinel-2 B08 (842 nm) and B04 (665 nm) bands. They found that Sentinel-2 satellite images were effective in identifying plastic clusters in the sea, through the high reflectance of solar radiation at NIR wavelengths. They highlighted that future research should focus on the use of Sentinel-1 SAR images for the identification of plastic litter in the seas.

Antonioli et al. [104] studied the relative sea-level rise and potential submersion risk for 2100 on 16 coastal plains of the Mediterranean Sea (France, Spain, Tunisia, Cyprus) by analyzing LIDAR data and different climate projection scenarios. They estimated a potential loss of land for the above areas between about 148 km^2 for the IPCC-RCP8.5 scenario and 192 km^2 for the Rahmstorf scenario, impacting a coastline length of about 400 km. However, the low resolution (25 m ×25 m) of the Digital Terrain Model map of Cyprus prevented any further detailed coastal hazard assessment.

3.3.9. Big Earth Data

The Big Earth Data thematic area includes technologies and development of methods and algorithms which are applied in the other thematic areas. Thus, it is considered as a horizontal thematic area. Nine out of the ten most highly cited articles which include Big Earth data applications were already described in subsection 3.1.5 and the focus of these papers is on the use of Machine learning and Artificial Neural Networks on landslide and flood studies. The remaining article focuses on a novel machine learning-based approach for the risk assessment of nitrate groundwater

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contamination [34]. Three machine learning models including boosted regression trees (BRT), multivariate discriminant analysis (MDA), and support vector machine (SVM) were used for the probability of groundwater pollution occurrence and then an ensemble modeling approach was applied for production of the groundwater pollution occurrence probability map with reliable results. The majority of the research done on Big Earth Data in the EMMENA region is applied.

3.3.10. Other

This study also identified EO studies in the EMMENA region which are not included in any of the above thematic areas. These studies include animal species detection, identification and monitoring [105–107], sociodemographic characteristics [108,109], spatial analysis of cancer [110,111], optimal siting of electric vehicle charging stations [112], evaluation of bike-share stations [113], paleoecology [114] and examining the walking accessibility, willingness, and travel conditions of residents [115].

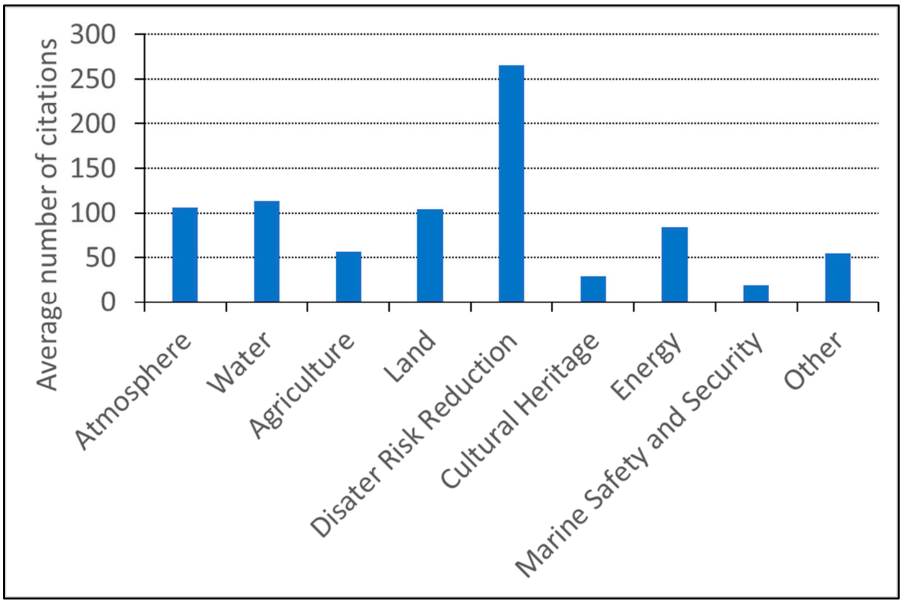

Figure 4. Average number of citations per thematic area (top 10 cited papers).

4. Overview and Conclusions

Over the past years, there has been an increasing trend in EO research in the EMMENA region (Figure 5). However, the number of EO studies in the EMMENA region represents only 3% of the EO studies carried out worldwide. Also, as we have shown in Table 2, the number of EO is highly uneven between countries within the EMMENA region. Iran is the most active EMMENA country in terms of EO publications, as shown both from the number of publications and the author affiliations. The recent establishment of a Centre of Excellence acting as digital innovation hub for EO in the EMMENA region is a significant advancement in expanding EO research and in seeking future collaborations and knowledge transfer schemes among the EMMENA countries [116].

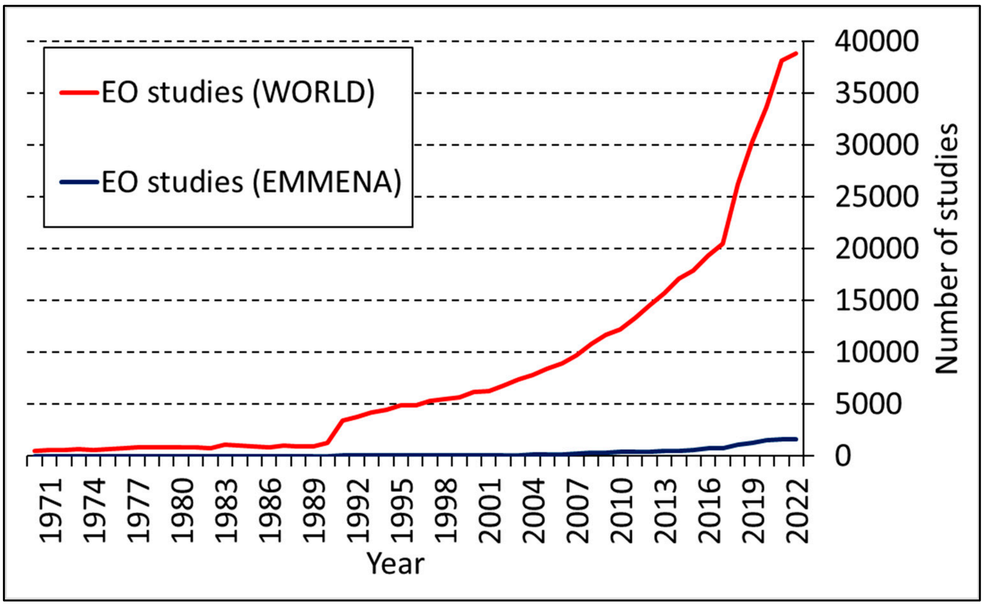

Figure 5. Number of EO publications per year for the EMMENA region (blue line) and the World (red line).

Research in specific thematic areas is surprisingly limited. The Mediterranean Sea is one of the busiest seas in the world, harvesting 20% of seaborne trade and over 200 million passengers [117]. In addition to this, the Mediterranean Sea is exposed to many risks such as rising CO_2 emissions, pollution, marine litter, and collisions. However, this is not reflected by the number of studies done on Marine safety and security thematic area. We speculate that the reason for the low number of studies in this thematic area may be twofold: restrictions in data sharing which often applied in the sea region due to security reasons and the insufficient resolution and revisiting time of existing non-commercial satellites which limits their ability to detect objects and the movement of these objects in time. Similarly, EO applications in Cultural heritage thematic area are very low (1.4% of all EO applications) with the insufficient resolution of existing non-commercial satellites being identified as the main limitation.

Most studies on the water thematic area focus on groundwater research, as shown both by the article review and the results of the citation topics. However, there is a range of topics where EO applications can contribute such as monitoring of lakes, dams, and rivers. In addition to this, the management of transboundary rivers at a watershed level will be an emerging issue as water resources continue to diminish in the EMMENA region. Thus, EO applications may become a necessity in the emerging topic of Hydrodiplomacy.

Another major limitation in the EO application is the lack of harmonized methodologies in specific scientific domains. This is particularly evident in the thematic areas of water, disaster risk reduction and energy where studies use different data inputs, methods and algorithms in order to reach the same research outcome. Future studies should focus on the development of standard protocols which will guide researchers and stakeholders towards the selection of the most suitable method based on the specific characteristics of their research. Furthermore, the plethora of satellite data currently available are usually scattered among different platforms resulting in extra amount of time and work for data collection and preprocessing [18]. The development of a central data hub (or data cubes) can resolve this issue. An example of such a central data hub is the GEO-CRADLE EU project which facilitates access to and sharing of geospatial data and information collected from satellites and ground-based networks in the North Africa, Middle East, and Balkans (NAMEBA) region.

Services related to early warning and decision support systems will upgrade EO applications especially in thematic areas dealing with hazards and human health [65,69,101]. The improvement of existing services or the continuous development of new systems will help stakeholders and the relevant authorities to take the appropriate actions aiming at reducing the number of human casualties and severe economic losses. Similar systems will be extremely useful in the thematic areas of Atmosphere and Agriculture, with applications regarding weather extreme warnings and irrigation support.

Other limitations in current EO applications identified in this research is the lack of freely accessible VHR images with sufficient temporal resolution, the lack of in-situ observations for EO verification and the lack of fundamental research in the domain of Big Earth Data.

The results of this study will benefit researchers as it provides an extensive review on the current applications, knowledge gaps and future directions of EO applications in the EMMENA region. It can also serve as a "tool" for those seeking collaborations with well-established scientists and institutions on EO science within the EMMENA countries.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: List of publications including author name, article title, author keywords and affiliations, times cited and DOI.

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