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The challenge of adopting mitigation and adaptation measures for the impacts of sand and dust storms in Eastern Mediterranean Region: a critical review

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Abstract
Sand and dust storms (SDS) are a major disruptor in both the source areas where they occur and at distant locations. This critical review aims to address the question of whether mitigation and adaptation measures have been or can be implemented and what is the optimal scale of their implementation to negate the impacts of SDS in Eastern Mediterranean Region (EMR)? Measures which differ in approach are also assessed by recording their successes, failures, and future challenges. We conclude that developing and implementing appropriate mitigation or adaptation measures for SDS at the local level is feasible but, at a wider scale, is a new challenge. This challenge is even more complex in areas like the EMR and the SDS sources affecting it, as it is a crossroad of air masses originating from three major SDS areas, which exhibit economic, political, and social diversity. This review also aims to identify successful mitigation strategies that have been used for similar environmental issues and to draw attention to the lack of adaptation measures in the region. This critical synthesis will serve as a guide for public stakeholders considering measures to mitigate or adapt to SDS based on their effectiveness and the area of implementation.

Keywords Desert particles · Erodible land surfaces · Future pressures · Socioeconomic and political dimensions · Transboundary air pollution

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1 Introduction

Air quality is of critical and rising importance, as widely acknowledged by the World Health Organization (WHO) and many other International and National Public Health Organizations, because 4.2 and 3.8 million premature deaths annually are associated to exposures to ambient and indoor air pollution, respectively (WHO 2016). Previous studies have attributed the increasing trend of both disability-adjusted life years and mortality in various areas of the world to the increasing emission rates of anthropogenic and natural air pollutants in relation to other factors such as population ageing (Babatola 2018; Cohen et al. 2017; Lelieveld et al. 2015).

Of all the major air pollutants that affect human health, particulate matter (PM) exhibits the most multi-scale and multi-variable behaviour (Betzer et al. 1988; van der Does et al. 2018), due to its multiple physicochemical characteristics and emission mechanisms. Emissions of sand and dust particles in the atmosphere usually emerge from hyper arid, arid, or semi-arid areas with barren surroundings and low or no vegetation, such as deserts, which are also characterised by the prevalence of strong winds and low or no moisture (Choobari et al. 2014; Ghose 2002; Middleton and Kang 2017; Thomas et. al. 2005; Webb and Pierre 2018). However, such sources are not located only in uninhabited areas, but also in places where many human activities occur. Agricultural areas in Niger that have been degraded due to droughts (Abdou 2013), open mining areas, and abandoned mines in Colombia and Australia (Huertas et al. 2014; Tordoff et al. 2000) are such distinctive examples. In particular, agricultural activities and overgrazing have caused a land change in vegetation and cover, which, under certain meteorological conditions of wind speed and moisture, lead to sand and dust storms (SDS) (Gill 1996; Liu et al. 2015). Interestingly, Mahowald et al. (2010) used ice, coral, and lake cores close to the main source areas (dust paleodata) to show that dust emissions doubled in the twentieth century because of human influence. However, as the same study indicates, other reports have recorded a −20 to +60% variation in the anthropogenic effect on desert dust emissions, demonstrating the uncertainty and importance of further research in this field.

The World Meteorological Organization (WMO) defines SDS as ‘an ensemble of particles of dust or sand energetically lifted to higher elevations by a strong and turbulent wind’ (WMO 2021). Many effects of moderate or high intensity SDS, namely the impact of particles on human health and various economic sectors, have been systematically studied (e.g. Tsiouri et al. 2015). However, associated mitigation and adaptation measures are rarely studied. For example, only Middleton and Kang’s (2017) review and a large-scale report (UNEP et al. 2016) have gathered different impact mitigation and adaptation measures globally. The review paper and the report have not reported how directly affected countries in the Eastern Mediterranean Region (EMR) use or can use measures to adapt the phenomenon and how the economic, political, and social diversities in each area are important to be highlighted before implementing mitigation and adaptation measures.

The EMR and the sources affecting it are economically, politically, and culturally heterogeneous, and its geographic boundaries are not accurately defined in the literature. Therefore, challenges in implementing and evaluating mitigation and adaptation measures are even greater. In this review, the EMR refers to countries around the Eastern Mediterranean Sea, namely Cyprus, Greece, Israel, Turkey, Lebanon, Syria, and Egypt. This review examined mitigation measures in the source areas of the Middle East, Northern Africa, and the Sahel, where SDS originate and do not belong to the pre-defined countries of the EMR, whereas the adaptation measures are examined in the EMR countries as shown in Fig. 1. The term ‘measure’ refers to a single or a series of actions at a local or at a wider scale. The aim of this paper is to review the different mitigation and adaptation measures that are taken or can be taken

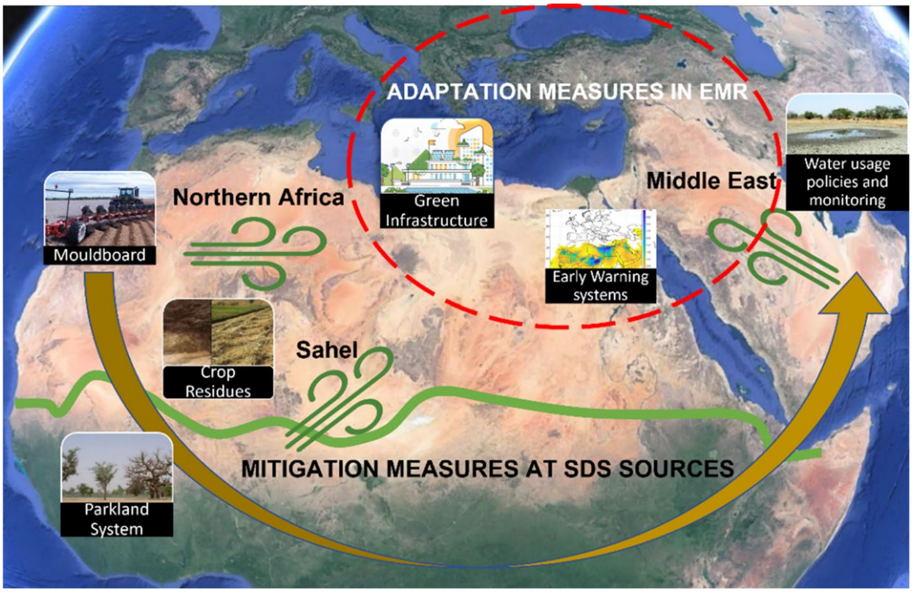

Fig. 1 The graphical representation of the assessment of mitigation and adaptation measures, as well as the presentation of the investigation areas

in the source areas of SDS or the EMR in order to negate the impacts of SDS locally or far away, while investigating the challenges of implementing the measures by the different social, economic, and political dimensions' future challenges.

The search strategy used to conduct this critical review included the Scopus, Web of Science, and Google Scholar databases. In addition, the websites of European and non-European environmental agencies were searched for case reports, editorials, scientific papers, and critical reviews published in English from 1984 to 2023. The keywords dust, impact mitigation, mitigation and adaptation measures, transboundary emissions, Eastern Mediterranean Region, Sahel, Middle East, and Northern Africa were used.

This paper is structured as follows: Section 2 provides the reasoning behind the investigation of SDS in the EMR; Section 3 briefly reviews the impacts of SDS; Sections 4 and 5 present the different mitigation and adaptation measures in the study area; Section 6 examines the socioeconomic and political aspects of implementing the measures; Section 7 discusses the future pressures that can affect the implementation of measures; and finally, Section 8 summarises the key conclusions of this review.

2 SDS in Eastern Mediterranean Region

DS have been reported since ancient times; the historian Herodotus reported that an SDS in 525 B.C. buried the army of the Cambyses (Herodotus III: 86–88) either from hearsay or the aftermath of the event. In the modern era, the methods of identification, monitoring, and analysis, as well as the understanding of the mechanisms that govern SDS, have improved. Despite the different characteristics of the sources, they share a common feature, which are the erodible surfaces.

The wind erodibility of ground surfaces is controlled by various factors, such as the land cover (e.g. vegetation and rocks), characteristics of individual soil types (e.g. texture), or biological compositions, which can be of importance in sand and dust emissions (Katra et al. 2017; Soil and Water Conservation Society 2017; Zobeck and Van Pelt 2015). In addition, other characteristics, such as topographic depressions or locations near the downwind side of mountain ridges (Cuesta et al. 2009; Doyle and Durran 2002), can be of importance in the emission of sand and dust. Once the particles are lifted to higher elevations, they are transported over long distances, subject to the prevailing meteorological conditions. Finally, the suspended particles are brought to the earth's surface, depending on the prevailing atmospheric conditions, by dry and wet deposition processes (Knippertz and Stuut 2014). Figure 2 shows the lifetimes of SDS.

SDS in the EMR originate more frequently from Northern Africa and the Sahel (North Africa) during spring, and during autumn from the Middle East (Gherboudj et al. 2017; Varga et al. 2014; Kubilay et al. 2000). The sources are separated in 3 types: (a) hydrological, referring to playas, ephemeral, and dried lakes, (b) natural non-hydrological, referring to areas with low land use such as sand and dust dunes, and (c) anthropogenic, referring to areas with high land use such as agricultural fields (Ginoux et al. 2012). In North Africa, the Sahara Desert is spanning from the Atlantic Ocean to the Suez Canal and from the Mediterranean Sea to the Sahel, consisting of the largest sand and dust source in the world. More than half of the global dust emission budget, around 500–1400 Tg year^{-1}, is emitted from this desert (Ginoux et al. 2004; Miller et al.2004; Tanaka and Chiba 2006), while Gherboudj et al. (2017) reported that more than twenty (20) source areas of SDS have been identified across North Africa. The Bodele depression, the Nubian Desert in Egypt, and the Saharan Atlas slopes are only some of the high dust emission areas.

In addition, the Middle East is situated between the three (3) areas of the Global Dust Belt, North Africa, and Central Asia, both of which are key SDS sources. This area is a mosaic of different source types ranging from the Euphrates-Tigris basin and the Syrian desert, stretching to Saudi Arabia and the Sistan basin, all of which are profoundly influenced by human activity through land use change and the construction of reservoirs (Rashki et al. 2012; Zender

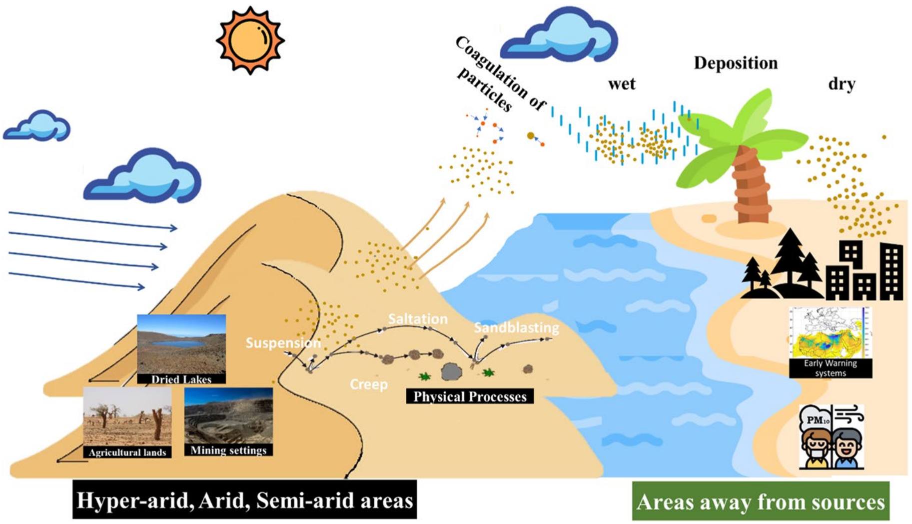

Fig. 2 Physical processes that lead to sand and dust emission and govern the lifetime of SDS

2003). From this area, it is estimated that the annual mean dust flux is between 40 and 500 Tg year^{-1} (Ginoux et al. 2004; Miller et al. 2004; Tanaka and Chiba 2006).

Meteorological conditions and climate variability have both been proven to have an exert influence on SDS. Bodenheimer et al. (2019) concluded that SDS of eastern origin are mostly related to the Red Sea Trough system while, Varga et al. (2014) identified that SDS of western origin are mostly related to Mediterranean cyclones during winter and Sharav cyclones during spring. Consequently, the SDS in the region can affect the air quality in mainland Greece, the North Aegean Region, Cyprus, Israel, and Turkey (Çapraz and Deniz 2021, Triantafyllou et al. 2020; Tsiflikiotou et al. 2019; Vratolis et al. 2019, Krasnov et al. 2016a; Mouzourides et al. 2015).

As a dominant phenomenon for EMR, SDS is being recorded by researchers in different studies in terms of their frequency and intensity based on very high-resolution ground and satellite data. For example, based on ground data from stations within Pey et al. (2013) records that in the whole Mediterranean Basin, the south-eastern part which includes the EMR has higher annual dust contributions than the west or the western part of the Basin. Furthermore, over a 49-year data analysis from 1958 to 2006, Ganor et al. (2010) found an increasing trend of SDS in the EMR. In addition, individual studies in specific areas have been monitoring the trends of SDS. For Cyprus, data between 1993 and 2008 from an urban station in Nicosia and a background station in Agia Marina found that average daily concentrations of PM_{10} during SDS have decreased from the year 2000 to 2008, even though the number of dust days has increased (Achilleos et al. 2014). In another instance, ground monitoring stations measuring PM_{10} concentrations in 3 cities of Israel between 2001 and 2015 identified more extreme concentrations PM_{10} due to SDS in the years after 2009 (Krasnov et al. 2016b). Lastly, Aslanoğlu et al. (2022) identified the climatology of dust in the area using CALIOP and MODIS satellite systems for a 9-year period (2007–2015) in Turkey. This study found that the eastern part is more affected than the western part of the country. In general, studies in the area were conducted without uniform methodology in different areas of the EMR. An exception was found in the literature, for example, Achilleos et al. (2020) focused on 3 sites simultaneously (Cyprus, Crete-Greece, and Israel) over a 12-year period from 2006 to 2017. Their study provides a holistic approach of identifying dust days with PM ground measurements, satellite products, and meteorological conditions. They also found that there is no increasing or decreasing trend, but rather a quasi-steady state of dust days in the area for the period of study.

Due to the variability in meteorological conditions, modelling and forecasting SDS is complex and significant SDS events in the EMR are the centre of attention and study. For example, a severe SDS over the Eastern Mediterranean that took place in September 2015 (cf. Figure 3) was missed by the operational models due these weaknesses (Mamouri et al. 2016; Solomos et al. 2017). The magnitude of this event, although rare, showed how many countries in the area can be affected, highlighting the need for adequate concerted efforts for mitigation and adaptation measures. Other significant events have also been investigated in the EMR as the 'Minoan Red' event in Crete-Greece during late March of 2018 (Monteiro et al. 2022) or the intense SDS in April of 2005 over Greece (Kaskaoutis et al. 2008).

3 Impacts of SDS

3.1 Negative impacts

Hazards due to SDS have been recognised in all three phases of the phenomenon, i.e. from the entrainment-lifting of sand and dust, to transport and deposition (Middleton 2017).

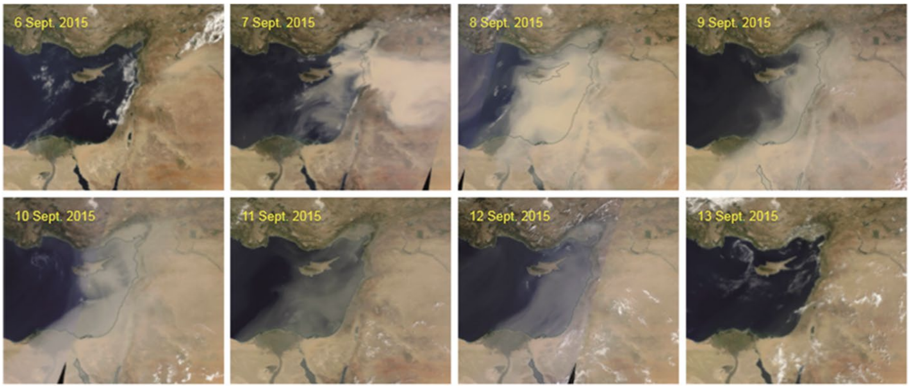

Fig. 3 Satellite images of the EMR as the SDS event progressed in September 2015, extracted from NASA Earth Observing System Data and Information System (EOSDIS), https://worldview.earthdata.nasa.gov

Hazardous impacts may be identified but are not limited to human and animal health (e.g. Vodonos et al. 2014; Neophytou et al. 2013a, b), satellite signals (Solheim et al. 1999), and air flights (Middleton 2017), whereas it may have a substantial impact on the performance of renewable energy infrastructure such as photovoltaic panels (Conceição et al. 2018; Saidan et al. 2016).

In drylands, where degradation is high (Reynolds et al. 2007), deflation removes the topsoil where nutrients are mostly found, reducing the productivity of agricultural areas and damaging young plant roots (Armbrust and Retta 2000; Mrabet 2002). Furthermore, damage to the plant leaf tissue due to sandblasting affects the overall growth and performance of the plants and consequently impacts agricultural production (Stefanski and Sivakumar 2009). Infrastructure is also affected by deflation in near-source areas, where the entrainment and transport of large quantities of particles occur (Huszar and Piper 1986; Wang et al. 2010). For example, in Kuwait, the annual cost of removing sand and dust from roads is \$9.36 million annually (Al-Hemoud et al. 2019).

The hazardous impact of SDS on human and animal health (Heal et al. 2012) increases in complexity in urban areas, where dust particles are mixed with anthropogenically emitted organic particles (Riemer et al. 2019) because of the particular airflow structures in compactly built areas and street canyons. Such airflow structures have been found to substantially enhance the accumulation of entrained particles transported over long distances and reduce the breathability capacity (Panagiotou et al. 2013) of urban streets, which can be thought of as the *lungs* of a city. Due to the reduced breathability capacity in highly compacted built areas, higher concentrations of particles are observed within street canyons than in other areas, resulting in the increased exposure of pedestrians and citizens to particulate pollution; such observations were made in laboratory experiments (e.g. Neophytou et al. 2014), computational simulations (e.g. Kubilay et al. 2017), and field measurements within urban street canyons of compacted built areas (e.g. Karra et al. 2017).

In the EMR, especially for countries such as Cyprus, Greece, and Israel, several studies demonstrated associations of PM_{10} levels during DDS outbreaks with increased total and case-specific mortality and hospital admissions for asthma and chronic obstructive pulmonary disease (Middleton et al. 2008; Neophytou et al. 2013a, b; Samoli et al. 2011, Vodonos et al. 2014).

Sand and dust particles can also negatively affect the hydrologic cycle and global radiative budget (Hui et al. 2008; Kaufman et al. 2005) because they act as cloud condensations and ice nuclei or absorb and scatter incoming solar radiation, respectively. Specifically, dust particles form longer-living shallow clouds and decrease the size of the droplets by 10–30%. As a result, they are further susceptible to evaporation by absorbed solar radiation, which in turn inhibits precipitation (Lohmann and Feichter 2005). Moreover, during the SDS deposition phase, dust particles can 'contaminate' water bodies by changing their chemical characteristics (Griffin et al. 2001).

3.2 Positive impacts

Positive effects of SDS have also been reported in the literature. Micron-sized particles (i.e. 1–20 μm) significantly affect the net change in the energy balance of the earth's system. Depending on their characteristics, particles can absorb or scatter solar radiation, causing a cooling effect in the atmosphere and ocean (Ginoux 2017; Lau and Kim 2007). Studies have reported that large sand and dust particles can act as greenhouse gases by heating the atmosphere (Kok et al. 2017; Mahowald et al. 2014). Similarly, large dust particles are effective cloud condensation nuclei when they are freshly emitted, mainly because of their size, and when coated with soluble or hygroscopic material as they age in the atmosphere (Choobari et al. 2014; Kumar et al. 2011; Levin 2005).

Positive effects have also been observed because significant amounts of nutrients are transferred across regions during SDS. For example, the cross-fertilisation of the Amazon forest, where the soil is low in nutrients due to high erosion from high rainfall, and the Bodele depression in Chad acts as one of its main nutrient sources (Ben-Ami et al. 2010; Koren et al. 2006; Swap et al. 1992). In addition, plankton and chlorophyll productivity in ecosystems is enhanced because of the settling of dust in the sea (Gallisai et al. 2014). Chlorophyll in the central and eastern Mediterranean was found to be affected mostly by sand and dust deposition, particularly during spring. Finally, sand and dust can be partly alkaline and negate the effects of acid rain (Han et al. 2011).

Overall, SDS have significant positive effects on the environment and ecosystems, and consequently on humans, indicating that mitigation measures must be designed and implemented to moderate their negative effects without disturbing the ecological balance.

4 Mitigation measures in the emission source areas

Sand and dust sources have different characteristics and are therefore subject to different mitigation approaches. This section overviews the mitigation measures and assesses their success or implementation challenges near-source areas. We should note here that mitigation measures are the means used in the source areas to prevent, reduce, or control SDS. In some cases, mitigation measures also include restitution for any damage to the environment caused by the emissions of sand and dust through compensation, replacement, restoration, or any other actions.

The mitigation actions reviewed in the following subsections, which have been applied at different scales, are structured based on the type of emission sources (Fig. 4). Table 1 summarises all the mitigation measures based on their applications at different locations. Evidently, the most systematic efforts to reduce dust episodes are mainly located in Central Sahel-Niger, Mali, and Burkina Faso. Few studies have been conducted on the Arabian

Peninsula, where sand and dust mitigation measures have been considered. The insufficient information on this subject in the Arabian Peninsula may be due either to the insufficient interest in mitigation measures or the limited publication of relevant activities.

4.1 Mitigation measures for wide-scale SDS

Large-scale and cross-sectoral actions in the societal, agricultural, and economic dimensions have been initiated in some source emission areas.

The massive planting of trees around the Sahel has been given a broader sense with the Great Green Wall (GGW) of the Sahara and Sahel. This initiative was first introduced in the 1980s and formally adopted in 2007 in the National Action Plans of several Sahelian countries (UNCCD 2016). This enormous plan comprises a 15-km-wide and 7775-km-long tree line from Dakar to Djibouti in order to reduce wind erosion, desertification, and ultimately SDS. As of 2020, some of the countries involved with the project have made significant progress in land restoration while others not so much. Specifically, in the UNCCD (2020) report, all 11 countries taking part in the project have reported financial challenges while governance, monitoring, and technical challenges were also identified between 2011 and 2017. Such forest plantations can fail for many reasons, e.g. from anthropogenic (e.g. lack of planning, injuries to young plants during planting, and unsuitable species of trees) and natural reasons (e.g. low rainfall and high temperatures (Jackson 1984). Thus, maintaining and monitoring a plantation in its early stages does provide with a higher survival rate. Although millions of trees have been planted along the GGW, much more planting must be performed, and the plan is expected to be completed in the next decades. Large-scale tree plantations, similar to the GGW in Africa, not only mitigate the effects of SDS but also reduce the effects of climate change by reducing the greenhouse gases in the atmosphere (Bastin et al. 2019; Benjaminsen and Hiernaux 2019).

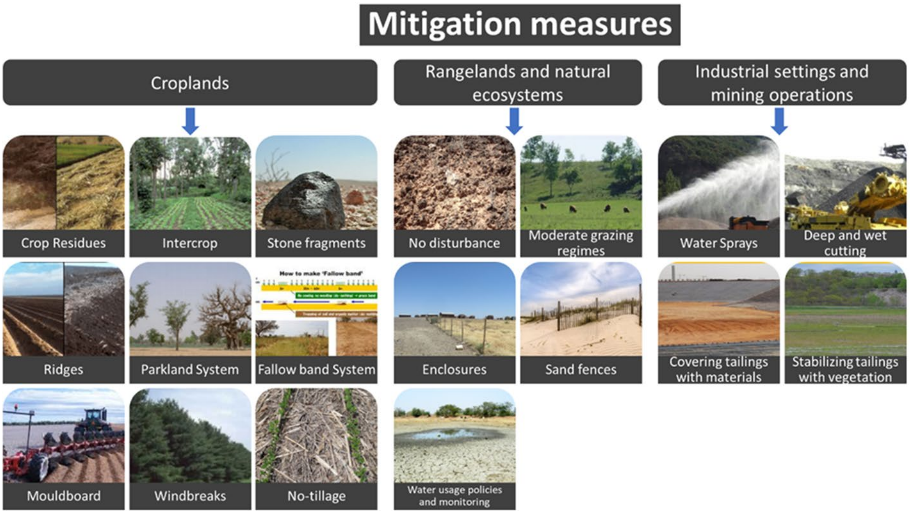

Fig. 4 Graphical summary of mitigation measures based on emission sources

Table 1 Summary of the mitigation measures found for the source areas based on their application

Source/location	Mitigation actions	Strategic points	References
Wide scale			
Sahel (Niger, Burkina Faso)	Farmer-Managed Natural Regeneration	Millions of hectares of land have been regreened Self-sufficient measures to promote stability	Reij et al. (2009) Pye-Smith (2013) Abdou (2013)
Sahel (Across Africa)	Great Green Wall for the Sahara and the Sahel	A large-scale plan to reduce desertification, wind erosion, and, ultimately, SDS	UNCCD (2016)
Sahel (Cameroon, Central African, Republic, Chad, Libya, Niger, Nigeria)	Lake Chad 2009–2017 restoration programme	Stability of dried areas and greening of land	ADF (2020)
Sahel	Soil and water protection and conservation schemes	Stabilisation of sand and restoration of areas and regreening	GIZ (2012)
Northern Africa (Morocco)	Green Morocco Plan	Harvest of rainwater and transplantation of rosemary to increase vegetation	Solh and Saxena (2011) Homrani Bakali et al. (2016)
Croplands			
Sahel	Crop residues	Significant reduction of erosion but not comparable results Very low crop residues are sufficient for reducing wind by a factor of 4	Sterk (2003) Abdourhamane Toure et al. (2011)
Sahel (Burkina Faso)	Parkland system	Shrubs reduced wind speed and sediment transport up to 7.5 times	Leenders et al. (2007, 2011, 2016)
Sahel	Fallow band system	Can effectively capture soil particles and coarse organic matter	Ikazaki et al. (2011)
Sahel	Windbreakers	Prevents wind erosion but can cause difficulty in agricultural practices	Sterk (2003)
Northern Africa (South Tunisia)	Mouldboard	Mouldboard has significantly better results in reducing wind erosion than other means	Labiadh et al. (2013)
Northern Africa (Tunisia Morocco)	No-tillage method	The no-tillage practice can decrease wind erosion and increase soil organic carbon	Ben Moussa-Machraoui et al. (2010) Mrabet et al (2012) Moussadek et al. (2014)

Table 1 (continued)

Source/location	Mitigation actions	Strategic points	References
Northern Africa (Morocco)	Intercrop	Trees among crops can help prevent soil erosion	Daoui and Fatemi (2014)
Middle East (Northern Syria)	Zero tillage and crop residues	Conservative agriculture techniques, increased soil organic carbon and decreased wind erosion	Sommer et al. (2014)
Middle East (Northern Syria)	Crop residues	All residue treatments have a positive influence on soil organic matter and improve soil properties and moisture levels	Sommer et al. (2011)
Middle East (Jordan)	Stone fragments in fields	Using 5% and 15% stone fragments in a field can reduce soil erosion by 35% and 53%	Abu-Zreig et al. (2011)
Rangelands			
Sahel (North Ethiopia)	Enclosures	Enclosures of areas for preventing grazing have produced very good restoration results	Yayneshet et al. (2009) Gebrehiwot and Veen (2014)
Northern Africa (Southern Tunisia)	Sand fences	Sand fences from palm leaves were built next to a road, to create a dune and enable sand-dust deposition	Wiggs (2011)
Northern Africa (Mauritania)	Water usage	Use of treated sewage and unadulterated seawater for sand dune stabilisation	Badescu and Cathcart (2010)
Middle East (Iran)	Water usage policies and monitoring	Measures that have contributed considerably to stabilising the water level	ULRP (2018) Danesh-Yazdi and Ataie-Ashtiani (2019)
Middle East (Israel)	No disturbance	Microphytic communities in the northern Negev Desert form a biological crust that further enhance the stabilisation	Veste et al. (2001)
Industrial setting/mines			
Not found	-	-	-

To reverse the adverse effects of significant losses of fertile land due to desertification and population pressures, the ‘Maradi Commitment’ was established in Niger in the 1980s, wherein a block of 10 ha in each city was planted with trees (Larwanou et al. 2006). Additionally, farmers were urged to use the trees naturally growing in their fields as soil stabilisers and as a source of fuel and food for livestock through continuous harvest techniques under a programme called Farmer-Managed Natural Regeneration (Abdou 2013). Furthermore, the government of Niger adopted the 3N initiative, *Nigeriens Nourishing Nigeriens*, to promote sustainability and combat poverty, land degradation, and hunger (Abdou 2013). Today, villages have 10 to 20 times more trees than at the beginning of the programme, and 5 million ha of land is estimated to have been regreened (Pye-Smith 2013; Reij et al. 2009).

Degrading lake systems and drying rivers can result in the exposure of soft sediments, as in the case of the Bodele depression in the Sahel region, which is one of the biggest sources of sand and dust. The lake was part of Mega Lake, Chad, which once covered 350,000 km^2 (UNESCO 2004). Since 1950, the lake went through different dry states up to 300 km^2 in the 1980s, exposing much of its highly erodible sediment and degrading nearby agricultural lands and pastures because of climate variability and human intervention (Galeazzi et al. 2017; LCBC 2016; Mahmood and Jia 2019). Millions of individuals reside in and depend on the area; therefore, in 2009, measures were implemented through the Lake Chad Basin Sustainable Development Programme to reverse the degradation situation. At the end of the programme in 2017, local plants covering 148 ha stabilised the dunes, and new agricultural and pastoral lands were developed (ADF 2020). Notably, other soil and water protection programmes and conservation schemes adopted in the Sahel aimed to stabilise the blowing sand from dunes, fence off areas that have been restored, and plant trees. These aims have been successfully executed due to German cooperation and funding from African projects (GIZ 2012).

In Northern Africa, the southeast rangelands of Morocco were restored by harvesting rainwater and transplanting rosemary, which increased vegetation, serving the needs of the local population (Homrani Bakali et al. 2016). This action was part of the Greater Green Morocco Plan that started in 2008, which attempted to increase agricultural production and the income of farmers as well as to ensure sustainable development (Solh and Saxena 2011).

The area with the least amount of intervention was the Middle East. The only relevant reference found in the literature review was the signing of a memorandum agreement between Iran and Iraq in 2011 (Ganjalinejhad et al. 2018) to facilitate the management and control 1 million ha of deserted land, but whether the plan was implemented was unclear.

4.2 Cropland

Croplands provide another significant source of SDS, and actions are implemented by farmers and scientists to reduce soil erosion and increase crop yield. There are many cultivated land areas in the source regions of the Sahel, Northern Africa, and the Middle East (Ginoux et al. 2012). The incorrect or limited use of best practices to prevent soil erosion can have many disadvantages, as highlighted by Govers et al. (2017). In the source areas investigated, the soil condition was poor, and the trend of soil erosion was increasing, making them susceptible to desertification (FAO and ITTPS 2015).

Soil management techniques and barriers have been used for reducing the loss of nutrient-rich topsoil in croplands. Bielders et al. (2001) examined the use of ridges perpendicular to the prevailing wind direction, showing a drastic decrease in soil erosion by 57%, and that reducing the spacing between the ridges increased their effectiveness in an on-farm experiment in Southwest Niger. However, this practice had a short life span due to rainfall and thus requires continuous maintenance, especially in the sandy soil types of the Sahel (Fryrear 1984).

Mulching is another countermeasure to wind erosion and was first implemented in Niger. Nigeriens used manure and crop residue to cover sandy soil. However, due to the different methodologies used in the studies, their mitigation effects could not be accurately determined (Sterk 2003). To evaluate the effectiveness of this measure, Abdourhamane Toure et al. (2011) investigated the quantity of crop residue required to control wind erosion by monitoring the erosion flux over 2 years. The results showed that generally low crop residues of approximately 100 kg ha^{-1} or approximately 2% of the total cover are sufficient for reducing wind erosion by a factor of 4.

In another practice, parkland systems in Burkina Faso (i.e. landscapes where scattered vegetation of trees and shrubs can grow) are sustained in cultivated or recently fallowed fields (Leenders et al. 2016). Shrubs were found to reduce wind speed and sediment transport by up to 7.5 times (Leenders et al. 2007; 2011). Intercropping, parkland-style vegetation with trees among crops, as practiced in Morocco can also help reduce soil erosion, as indicated by Daoui and Fatemi (2014). In contrast, changing rangeland to agricultural land can increase wind erosion and contributed to a net soil loss of 62 Mg/ha per year, which is five times more than the tolerable soil loss rate for the area (Houyou et al. 2016). Thus, exploitation of land for crop cultivation can lead to increased erosion if appropriate measures are not implemented to mitigate it.

The use of trees as windbreaks for crop protection in croplands is a common practice, and they can also act as soil stabilisers. The fallow band system, which was also applied along the Sahel, comprised herbaceous windbreaks that were 5-m wide and were placed against the erosive wind direction from the rainy to the dry season. This fallow band system has shown that over 3 years, it can effectively capture soil particles and coarse organic matter (Ikazaki et al. 2011). Tree-windbreakers have also been used in the Sahel, and Sterk (2003) indicated that trees can inhibit wind erosion. However, several limitations have been observed, such as the competition of trees for water and nutrients with the crops, solar radiation, cattle grazing, and land tenure concerns.

In addition to the aforementioned passive measures, agricultural machinery can play an influential role in soil stability. An experiment was performed in South Tunisia to assess how the use of different machinery tillage approaches affects soil erosion. The findings demonstrated that using a mouldboard attached to a tractor in cultivated fields had significantly better results in reducing wind erosion than using tractor discs or tillers as part of conventional tillage techniques (Labiadh et al. 2013). Additionally, in Morocco, decreased wind and water erosion was observed when minimum disturbance equipment, no-tillage methods, no-till disc drills, and dry seeding methods were used as part of the conservation tillage techniques (Mrabet et al. 2012). Generally, the complete removal of residues reduces crop yield because of high erosion (Mrabet 2002). Furthermore, Bot and Benites (2005) reported that increased soil organic matter and erosion control can be achieved. Ben Moussa-Machraoui et al. (2010) showed that under different crop types, the soil organic carbon and matter were enhanced when no-tillage practices were used, compared with their levels while using conventional tillage in a 4-year study in northern and north-western Tunisia. These results agree with the findings of Moussadek et al. (2014) in Central Morocco, where the use of no-tillage practices for 5 years increased soil organic matter from 2 to 10% in two major soils, vertisol and cambisol. Likewise, in the Middle East, and specifically in Northern Syria, zero tillage and crop residue measures were applied from 2008 to 2012 in different experimental crop fields to assess the difference between conventional and conservative tillage. The results showed that in conservative agriculture, high soil organic carbon and microbial biomass were observed, showing the potential for decreasing erosion (Sommer et al. 2014). Moreover, all residue treatments had a positive influence on soil organic matter and improved soil properties and moisture levels (Sommer et al. 2011). An additional example of soil loss reduction is the use of stone fragments in Jordan. Abu-Zreig et al. (2011) found that using 5% and 15% stone fragments in a field could reduce soil erosion by 35% and 53%, respectively. Some of the practices used for countering soil loss are also helping with crop yield, if used correctly. Stone fragments are found to increase crop yield in various cases and hold moisture in the soil, while they help with surface runoff and erosion (Nyssen et al. 2006; Katra et al. 2008). On the other hand, large stone fragments are found to be reducing crop yield (Chow et al. 2007). Considering the area of application, a mitigation measure can have the opposite effects if not applied properly.

4.3 Rangelands and natural ecosystems

Addressing the changes to rangelands and natural ecosystems, which may change SDS because of anthropogenic and natural intervention, through various measures is essential. One third of humanity lives in rangelands and drylands where semi-arid or arid climates persevere, covering more than 40% of the land area. Consequently, their stability is crucial for human survival (Reid et al. 2014; Safriel et al. 2005; Middleton and Thomas 1997). Moderate grazing regimes in a nomadic style are likely to improve rangeland regeneration rather than ranching or stocking rates, according to a long-term study of monitoring vegetation between 1981 and 2007 in the central Sahel (Miehe et al. 2010). In North Ethiopia, enclosure strategies to prevent grazing have produced very good restoration results (Gebrehiwot and Veen 2014; Yayneshet et al. 2009).

Furthermore, 31% of SDS on a global level are attributed to hydrological sources, such as river valleys, alluvial fans, and playas (dried lakes) (Ginoux et al. 2012; Goudie 2018). In Iran, Lake Urmia is an example of the anthropogenic influence on water bodies and their desiccation: the lake was severely downsized because of overconsumption and the building of dams, reducing it to 2366 km^2 by 2011 (Ouria and Sevinc 2016; Garousi et al. 2013). With 88% of its water cover lost from approximately 2000 (AghaKouchak et al. 2015), an estimation of a 30–60% increase in PM$_{10}$ in nearby cities was recorded (Sotoudeheian et al. 2016). To counteract this decline, the Urmia Lake Restoration National Committee was established in 2013, to devise and implement a plan to stabilise the decline and restore the lake through a series of measures. These measures comprised a decrease in agricultural land and, consequently, the use of agricultural water, additional water release from the dams to increase the water level of river valleys, and the control of the illegal withdrawal of water from the lake (ULRP 2018). In 2016, the water level was stabilised, and other actions, such as replacing the old irrigation systems with new, efficient versions, showed that the Urmia Lake Restoration plan has contributed considerably (Danesh-Yazdi and Ataie-Ashtiani 2019). However, Zucca et al. (2021) indicate that many of the reported mitigation measures of SDS impacts from hydrological sources are just mentioned as possible solutions based on statistical or other observations without any evidence of successfulness. In the review, a list of Sustainable Land and Water Managements (SLWM) practices are identified based on their nature of application, intervention zone either upstream, playa or downwind, and importance, with the help of the World Overview of Conservation Approaches and Technologies. Examples of high importance are integrated watershed management planning and implementation as an approach for all 3 intervention zones, improved water use efficiency as technologies related to water primarily for upstream and playa zones, and windbreaks as technologies related to wind and water erosion for playa and downstream zones.

Sand dunes cover large parts of natural ecosystems, such as deserts, and their formation is controlled by sand supply, wind regimes, and vegetation (Lancaster 2011). Significant shifting patterns in sand dunes have been associated with the topography and regional atmospheric circulation of an area (Washington et al. 2006). Furthermore, in arid areas, the chemical composition of sand dunes plays a significant role in wind erosion reduction; for example, the Negev and Sinai deserts contain 17% silt and clay, enabling them to be stabilised naturally (Tsoar and Zohar 1985). The microphytic communities in the northern Negev Desert form a biological crust that enhances stabilisation (Veste et al. 2001), thus not disturbing the areas can be crucial.

Additionally, anthropogenic interventions, such as the formation of sand fences from palm trees next to a road in southern Tunisia (Wiggs 2011) and the use of unadulterated seawater and cleaned urban sewage in Mauritania (Badescu and Cathcart 2010) to stabilise sand dunes, constitute sustainable practices to reduce wind erosion in natural ecosystems such as deserts.

4.4 Industrial settings-mineral operations

Mitigation measures are not only those directly related to natural sources and ecosystems but also those applied to sources related to large-scale anthropogenic activities such as mining and industrial operations. Fugitive dust from mining or industrial operations can be more harmful than normal dust emissions from deserts because it can contain contaminants from chemical additives used for mineral extraction processes and heavy metals (Csavina et al. 2011, 2012). An example is arsenic: 40% is emitted from smelting operations (Alloway et al. 1997). Dust particles from mining operations have been found to contribute significantly to suspended particle concentrations, 25% of which are respirable (Zota et al. 2009) and are mainly emitted from haul roads, tailing beaches, and slope areas (Park et al. 2019).

Despite the reports on emissions from mines in the dust source areas examined, such as in Mali and Niger (Garrison et al. 2014), Iran (Monjezi et al. 2009), and Algeria (Mokadem et al. 2014), no mitigation measures have been reported. However, such measures have been applied (e.g. Park et al. 2019) in areas not covered by this review. Nevertheless, they are briefly cited as examples or recommendations as follows:

i. Water spraying on tailings
ii. Covering tailings with other materials
iii. Stabilising tailings with vegetation
iv. Stabilising tailings with chemicals

The use of chemicals (e.g. biopolymers for stabilisation) was found to be more effective in enhancing moisture retention than using only water spray on tailings (Chen et al. 2015). Furthermore, phytoremediation, used in the USA as a measure of controlling dust emissions from tailings, showed a decrease in dust particle emissions and was comparable to the emissions from undisturbed grasslands (Gil-Loaiza et al. 2018).

5 Adaptation measures

Except for large-scale forecasting, covering the entire EMR region, we found no other wide-scale adaptation measure in the literature. On these grounds, small-scale and personal adaptation measures are recommended.

5.1 Monitoring and forecasting of SDS

An intermediate step for the implementation of other adaptation measures, highlighting the necessity and usefulness of monitoring and early prediction of SDS in areas far from emission sources, is important. Monitoring of SDS has always been conducted using long-term sand and dust observations and meteorology (Goudie and Middleton 1992). Before the advancement of atmospheric modelling and remote sensing, the categorisation of SDS severity was established based on the intensity of wind speed and reduction of visibility (Joseph et al. 1980; Xin-fa et al. 2001).

However, current technological and scientific progress has enabled scientists to monitor and predict SDS. The monitoring of sand and dust was recorded mainly by the ground stations. Networks such as the European Monitoring and Evaluation Programme include background stations that are located far from anthropogenic sources to record pollutants from long-range distances. Continuous monitoring is conducted at each site by using high temporal resolution equipment, such as a tapered element oscillating microbalance. These monitoring techniques are useful for evaluating models worldwide (Eleftheriou et al. 2021). AERONET, which employs a network of sun photometers (Holben et al. 1998), is another example of an observational system. Orbital or geostationary remote sensing platforms such as MODIS, SEVIRI, and CALIPSO also provide many satellite products with atmospheric aerosol properties at various temporal and spatial resolutions (Paz et al. 2013). Despite their great capabilities, monitoring techniques have limitations because most of them cannot provide the source apportionment of the particles in real time. In addition, sun photometers and lidars cannot perform reliable measurements during intense dust events (Fernández et al. 2019), and providing reliable satellite products is difficult when the atmosphere is cloudy, smoky, or dark.

Additionally, regional-scale forecasting of SDS requires the modelling of complicated physicochemical processes that occur in the environment. This finding implies methodological variability (various methods and databases, i.e. ground observations, satellite products, weather, and dust models), different levels of complexity, and ultimately significant uncertainty in forecasting. This uncertainty is due to many reasons, such as the lack of sufficient evaluation measurements appropriate to enable the confirmation of different stages (e.g. emission and deposition schemes) in the modelling processes, sub-grid variation causing differentiation in the friction velocity, particle size distribution, and the development of satellite methodologies (Shao and Dong 2006). Moreover, due to the use of 'static' land use and cover databases of SDS at sources, seasonal variations in land are not considered. In recent years, attempts have been made to produce dynamic SDS source databases (Kim et al. 2013; Solomos et al. 2019; Vukovic et al. 2014).

Such large-scale forecasting data is being hosted on online databases such the Sand and Dust Storm Warning Advisory and assessment System (SDS-WAS) which was established by the WMO in 2007 and is hosted in Spain for the European, African, and Middle East regions and in China for the Asia/Central-Pacific region (SDS-WAS 2020). Nowadays, a new updated platform is used the WMO Barcelona Dust Regional Center (https://dust.aemet.es/) and this centre is responsible for the research activities and operations of the WMO related to SDS. This online database hosts many, if not all, of the available operational dust models which are updated on a daily basis. Each individual model is run by a different country/authority/institution with different input data and modelling processes, resulting in varying outputs of dust concentration on the same area of interest.

In a long-term intercomparison of models with satellite products, substantial discrepancies have been recorded among several global- or regional-scale models (Evan et al. 2014). The lack of observations of soil characteristics (e.g. size and mineralogy) and gaps in meteorological conditions at source areas, which are important for modelling SDS, can result in differences among models (Benedetti et al. 2018; Roberts et al. 2015; Menut 2008).

Overall, monitoring and forecasting tools are used and can be used as adaptation measures to provide necessary warnings for individuals to be protected from incoming SDS, especially SDS. However, as reported in the literature, many concerns must be resolved to obtain the most timely, correct identification of SDS and their severity.

5.2 Personal exposure and protection and the reliance on early warning systems for SDS

Historically, SDS have not been considered harmful to humans, because of their natural origin and crustal composition. In line with this approach, legislation of the European Union considers SDS impossible to prevent, implicitly harmless, and discounts their contribution to the daily and annual air quality standards of PM_{10}. However, during the last two decades, several epidemiological studies from the EMR countries, such as Cyprus (Middleton et al. 2008; Neophytou et al. 2013a, b), Greece (Samoli et al. 2011), and Israel (Vodonos et al. 2014), have demonstrated associations of PM_{10} during SDS outbreaks with increased total and case-specific mortality and hospital admissions for cardiovascular diseases, asthma, and chronic obstructive pulmonary disease.

Currently, during SDS, competent authorities and mass media in the countries of the region issue non-standardised warnings to the general public and vulnerable groups, most commonly advising them to remain indoors and reduce outdoor activities. There is limited evidence on the societal concerns and risk perceptions for SDS and the health-related effects (Im et al. 2006). Only few studies examined the current knowledge and relevant practices of competent authorities or the knowledge and perceptions of involved social stakeholders in the region regarding the health effects of SDS (Kinni et al. 2021).

There is no scientific evidence on the efficacy of any of the recommendations in reducing exposure to SDS PMs or mitigating related health effects. The main goal of the demonstration project 'MEDEA' (Mitigating the Health Effects of Desert Dust Storms Using Exposure-Reduction Approaches; https://www.life-medea.eu) is to provide field-based evidence for the feasibility and effectiveness of adaptation measures to SDS in South-Eastern Europe, focusing on exposure reduction approaches. In this project, which is ongoing, exposure reduction is pursued by implementing both outdoor and indoor interventions (Kouis et al. 2021). For the outdoor intervention, children with asthma after receiving timely personal alerts and specific recommendations by smartphone and web-based applications and tools demonstrated significantly reduced outdoor exposure during SDS events by reducing time spent outdoors (− 28%) and reducing outdoor physical activity (− 13%) (Kouis et al. 2023). For the indoor intervention, children with asthma and adults with heart arrhythmias were asked to close windows and doors, seal possible cracks around windows and doors to minimise home ventilation, and use an air cleaner continuously to filter indoor air and managed to significantly reduce indoor $PM_{2.5}$ and PM_{10} by 43% and 41%, respectively, in comparison to the control group (Achilleos et al. 2023). In addition, anecdotal evidence from these studies, which is currently in the publication process, documented significant improvements in asthma symptom control in children and health-related quality of life in adults with heart arrhythmias. Implementation of interventions also depends on validated models for forecasting SDS in EMR, as well as early dissemination of warnings and audio-visual recommendations for exposure reduction via a web-based platform and smart mobile application to alert patients of upcoming SDS.

For the EMR, an early warning system, the SDS-WAS platform and now the WMO Barcelona Dust Regional Center as mentioned before, is commonly used. The concentrated expertise and data found on these online databases has proved valuable for competent authorities around the world to issue warnings for the public. Typically, the multi-model median (MMM) is being taken as an output or individual model based on each competent authority's experience or statistical analysis.

Exposure-reduction strategies have an important role in adaptation strategies. The employment of novel environmental epidemiology and telemedicine methods to assess personal compliance to recommendations, measure exposure to air pollutants in indoor and outdoor environments, and monitor clinical outcomes among the population is very important in the evaluation of these strategies. The methods previously employed in air pollution health effect studies have several inherent inaccuracies in assessing exposure and health outcomes. Exposure estimates are typically based on measurements conducted at sparsely distributed monitoring stations. These approaches use outdoor air pollution concentrations as a proxy for total exposure; therefore, they lack information on indoor air pollution levels, which introduces significant exposure errors (Baek et al. 1997; Hoek 2017; Leung 2015). Furthermore, exposure estimates are usually assessed for a given residential address, without considering participants' activity and mobility throughout the day (Park and Kwan 2017; Setton et al. 2011; Wu et al. 2011).

With modern technologies, wearable GPS and activity sensors can be used to continuously measure activity and time spent indoors and outdoors. This approach enables the assignment of exposure to the respective air pollutant levels measured in indoor and outdoor environments, differentiated by activity levels throughout the day, providing a high spatiotemporal resolution (Yarza et al. 2020). The health effects of desert dust exposure are typically assessed using ecological retrospective data on major outcomes such as death, hospital admissions, and outpatient clinic visits (Vodonos et al. 2014; Neophytou et al. 2013a, b; Samoli et al. 2011; Middleton et al. 2008). However, data on hospital admissions and outpatient clinic visits are influenced by subjective health care seeking behaviour and are therefore problematic in evaluating the onset, duration, and severity of an outcome (Yarza et al. 2020). With telemedicine methodologies, a range of clinical outcomes may be assessed beyond what standard tools, such as validated clinical symptoms questionnaires offer. In this context, health parameters such as heart rate, blood pressure, and oxygen saturation can be obtained from wearable sensors, and heart arrhythmias can be obtained from implanted pacemakers, providing continuous measures of a whole range of clinically relevant parameters that can be related to exposure to SDS.

5.3 Green infrastructure (GI)

The literature suggests a few GI-related adaptation measures for SDS in areas away from the sources. Therefore, adopting ideas and solutions that have been successfully implemented for similar environmental topics such as traffic pollution is necessary. GI, also referred to as nature-based solutions (NBSs; Debele et al. 2021), is a passive control measure, such as planting trees hedges, or shrubs to reduce air pollution (Abhijith and Kumar 2020; Kumar et al. 2019, 2022). For example, Abhijith et al. (2017) reviewed approaches and methodologies applied to open roads and street canyons and highlighted their benefits. For instance, trees in canyons with low porosity and high height can act as walls, trapping the pollution underneath them, forcing the air to flow above them, and thereby reducing air exchange (Abhijith and Gokhale 2015; Janhäll 2015). Therefore, trees can also be used to filter ambient air from dust or resuspended particles (Ottosen and Kumar 2020). Planting trees in compact urban areas to reduce air pollution and increase human welfare is not an easy task because many parameters need to be considered before committing to this action (Kumar et al. 2019; 2021).

Crucial parameters for consideration include, for example, the tree type, geometry of the area to be planted, and spacing between the trees (Barwise and Kumar 2020). Moreover, hair and waxes on certain types of trees (Sæbø et al. 2012), and the surface of leaves and their shape (Perini et al. 2017), influence the number of particles deposited on them, thereby increasing the accumulation of pollutants. Thus, GI can be of importance in adaptation measures because it can allow the deposition the atmosphere PM on them and mitigate against natural hazards such as flooding, landslides, and heatwaves (Debele et al. 2021; Kumar et al. 2020). The implementation of this measure, especially in an urban environment where the air quality is heavily burdened and buildings are much denser, must be carefully considered.

6 Social, economic, and political dimensions of mitigation and adaptation measures

Examples of how challenging the implementation of SDS mitigation and adaptation practices is can be realised when the socioeconomic and political aspects of each area are considered. For example, in most SDS source areas, the rural population is among the poorest worldwide, and there are many environmental problems such as land degradation, soil erosion, and the lack of water (Middleton et al. 2011).

Land degradation in drylands is caused by a number of natural and human-driven activities such as extreme climatic variations and overgrazing respectively (Davies et al. 2012; IUCN 2017). Grazing has been found in literature (Rowntree et al. 2004) to be of a complex desertification driver, as it is at the same time interacting with other factors affecting the area. These factors range from the perception of how beneficial grazing is for a country (Middleton 2018), extreme weather conditions and long-lasting droughts in drylands, to human activities such as the abandonment of cultivated land and tree cutting (Dregne 2002). Although overgrazing has been identified as a cause for desertification, pastoralism for example in the Sahel is an important occupation and composes a large sum of some countries' gross domestic product (Middleton et al. 2011). Thus, the control of overgrazing and its impacts promoting desertification needs to be enforced by the understanding and considering all the other accompanying factors described above for a holistic establishment of the mitigation measures in this instance. As Butt (2016) suggested, a more in-depth investigation of the impact of overgrazing than those in the literature must be conducted because pastoralists are being pushed into additional contained areas, which might lead to overgrazing. In addition, Beyene (2010) indicated that rangeland enclosures affect pastoralists' livelihoods and do not promote sustainability. Thus, the need for grazing control of livestock in such areas is in contrast with the need for individuals to survive with measures implemented to counter the overgrazing impact. Sahelian herders also have different characteristics based on being nomadic or sedentary; thus, their characteristics differ by when, where, and how their herds are led (Young et al. 2019).

The challenge of variability of herding practices can be faced through improved communication between stakeholders for the correct and sustainable exploitation of rangelands, which seems to have increased in the 2010s. However, the lack of law enforcement and trust between herders are examples of the factors that make it challenging to promote sustainability (Coppock et al. 2017; Turner et al. 2014). Opposed to overgrazing and degradation of land in the Sahel, actions have been put in place, and ground observations and reports have confirmed the increase in vegetation, but long-term assessments indicate that biodiversity is decreasing, which might affect the environment and livelihoods (Fensholt et al. 2017). In another instance, due to the introduction of commercial agriculture in the Sahel in the 1700s, dust deposition in alluvial systems has increased dramatically (Mulitza et al. 2010), indicating that the economic and social development of the area has resulted in the formation of an SDS source. This case is similar to that of the Senegal River, which provides more material to be blown away during periods of drought, showing anthropogenic influence.

Another implementation of mitigation measures through collective action was the successful application of the Lake Chad Action Plan, but major constraints were encountered that interrupted the smooth completion of the project (ADF 2020). Such constraints were the lack of competent programme experts, leading to the constant change in plans; the weak capacity shown by governmental services in performing tasks and supervision; the low organisation of surrounding communities in applying the measures; and insecurity. The insecurity in the Lake Chad area, linked to the water scarcity caused by the drought, is directly related to the socio-political instability of the surrounding countries, which drives the area into water conflicts and increases terrorism and insurgency, such as that of Boko Haram (Okpara et al. 2015). In addition, prolonged conflicts in the Middle East and Northern Africa can result in the deterioration of land and land use changes that can influence dust emissions (Jaafar and Woertz 2016). Similar challenges were also identified in GGW project, where challenges in governance are found due to the lack of environmentally friendly political agenda and lack of coordination between authorities and relevant sectors. Additionally, the absence of monitoring and evaluation data on the ground due to the lack of finance or the overwhelming work on governments creates lack of credibility towards investors, making it harder for new funding.

Moreover, in Libya, the change from agriculture to the oil industry after the discovery of oil provided a major flow of money in the economy, which funded many projects for the development of agriculture from the 1970s to the 1980s (Sachs and Warner 1999). Medium-term plans for agriculture were implemented with great success, but with the decrease in oil prices, annual plans were established with limited success, showing the influence of the economy on the successful implementation of plans (Allafi 2014). Additionally, the role of governance in securing sustainability is crucial in Northern Africa, as proposed by Ates et al. (2016); this is because the short-lived and sometimes harmful environmental practices remain incomplete. Thus, sound governmental input must overall be established in all cases. Furthermore, national plans such as the Green Morocco Plan, which attempted to ensure sustainability in rural territories, have failed to achieve their goals (Faysse 2015) because the information used as a baseline was inaccurate.

In the Middle East, Iran's Restoration Plan for Lake Urmia cannot be considered completely successful in terms of its goals, due to lack of data and deep understanding of the various physical processes of the anthropogenic and natural stressors of the lake. Specifically, data scarcity for certain parameters, such as land cover distribution, topography, and evapotranspiration, and those physical processes that have not been adequately understood, constituted some of the reasons that the restoration plan timetable of Lake Urmia was out of schedule (Danesh-Yazdi and Ataie-Ashtiani 2019). Furthermore, Salimi et al. (2019) indicated that the implementation of the restoration phase poses great challenges due to the contradictory national policy of agricultural development and the restoration of the lake reducing water consumption, the lack of proper funding, the weak local communities that need to change their water usage norms, and the future political instability of the country that might not prioritise this project.

External financing of projects having a great positive impact against land degradation and sustainable land managements is necessary as mitigation actions in areas with high poverty and scarcity of national funding as in the case of the GGW. The need for a certain level of global international governance is becoming more evident, and in the recent United Nations Environment Programme (UNEP) summit on Climate Change (2022) in Sharm El-Sheikh Egypt between 6 and 18th of November, the possibility of funding of a global/regional nature is being further introduced and established. The UNCCD (2020) progress report indicates that between 2011 and 2019, there is a notable discrepancy between external/international funding and national funding. Furthermore, there were a total of 870.3 million USD out of the 1.2 billion USD Sahel and West Africa Program (SAWAP) from international donors in support of the GGW project. This indicates how depended are SDS source countries on international attention and funding to proceed with successful plans. On the other hand, adaptation measures can be financed by national resources with early response mechanisms, green infrastructure, and training of the vulnerable groups with of the country that is affected through technology, making them more easily applicable and better monitored.

Regarding adaptation measures in the EMR, we found no literature on how effective the measures taken during SDS are. It is not clear whether these recommendations and warnings are established by employers or ignored because of lack of knowledge or lack of supervision from competent authorities. A recent study assessing interventions in reducing exposure to SDS indicated that compliance with adaptation measures is also dependent on behaviour, especially for children, and in school or at home (Kouis et al. 2021). Furthermore, NBS is based on co-approaches, that is, the cooperation of stakeholders at all levels and the disciplines involved in implementing them (Woods-Ballard et al. 2015). However, this interaction can reveal the perceptions of stakeholders, such as government bodies or landowners, which can cause major delays in the procedure, and their acceptance of the plan (Santoro et al. 2019).

The many conflicting interests with environmental goals have also been reported to be a problem in implementing NBS projects because developments in certain areas can be good for the short-term economy but bad for the long-term environment (Kabisch et al. 2016; Waylen et al. 2014). A common social dimension that must be considered when implementing measures is trust among stakeholders. As van Ham and Klimmek (2017) indicate, trust can be something that has been built or unbuilt during projects; thus, trust can be a decisive condition between success and failure.

In summary, in the implementation of mitigation and adaptation measures, the standard of living and culture of the affected individuals should be taken into important consideration. Values such as transparent governance, security, trust, and human welfare play an important role in the actual effectiveness of the implementation of measures. In addition, the scientific community also needs to provide a simpler context, because the context followed to date has been one of the reasons for the failures in measures' implementations (Dong et al. 2017).

7 Future pressures and approaches

Known or unknown future pressures are inevitable because of the changing norms of today, and new challenges will arise for leaders of nations and the world to manage. These pressures extend from climatic, socioeconomic, and humanitarian crises.

Simulations of climate change in source areas affecting the EMR show different results for changing temperatures and weather conditions; thus, different scenarios were investigated. The Mediterranean and West Asia will become drier, and the simulations of the Sahel will be inconsistent. Drier conditions on the ground could lead to lower monsoonal rainfall and thus longer droughts in the Sahel (Solmon et al. 2008; Yoshioka et al. 2007), which may further intensify SDS. From another perspective, a model experiment reducing SDS led to the enhancement of Saharan vegetation due to the extension of the West Africa Monsoon to the north (Pausata et al. 2016). Furthermore, observations have shown increased precipitation in the Sahel because of shorter, more frequent dry spells that can help the area's agriculture and resilience from droughts (Bichet and Diedhiou 2018). However, an increase in extreme storms has also been observed (Taylor et al. 2017); thus, a greater chance of SDS as convective storms is one of the generation mechanisms. The unpredictability of future climatic conditions must be considered when GI is used as an adaptation measure, because the increase in extreme events, such as heatwaves, droughts, and floods, can affect the selected vegetation used for air pollution protection (Bouwer et al. 2010; Forzieri et al. 2016).

Furthermore, with the increase of water needs as derived from the climate change simulations (UNEP et al. 2016), droughts may lead to conflicts (Feitelson and Tubi 2017). Upper riparian countries, such as Turkey, control the source of water for Tigris and Euphrates rivers, and without any agreements for water supply with the downstream countries, economic instability, migration, and insecurity are only a few of the problems that arise in such unstable areas (Al-Ansari 2016). Conflicts and hostile relationship between neighbouring countries sharing same hydrological resources can promote drought that controls politics and social behaviour, which among others burden the environment with additional sand and dust emissions.

Moreover, almost all countries worldwide have ageing populations because of declining fertility and increasing life expectancy (UN 2020). Related to climate change and the increase in extreme weather events (e.g. heatwaves), studies have shown that elderly individuals are more vulnerable to these conditions, increasing mortality (Chen et al. 2020; Hong et al. 2019). Additionally, deteriorating air quality, together with the potential increase in SDS due to climate change, can have an added burden on the ageing population (Simoni et al. 2015). Thus, competent authorities of affected countries need to be ready with their respective protection mechanisms, infrastructure, and organisation to adopt adaptation measures for SDS.

Last, Geist and Lambin (2004) in their meta-analysis on what drivers affect desertification found that in 73% of cases, a population increase and immigration of farmers towards rangelands or herders to marginal sites are the driving issue. For example, in Lake Chad, many individuals migrate to the area every season, increasing the pressure on the environment (Zieba et al. 2017).

Focusing on the future, the Sendai Framework for Disaster Risk Reduction 2015–2030 is an important framework. Adopted in 2015 at the Sendai, Japan World United Nation Conference, this framework gives emphasis on the disaster risk management aiming at 'the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries' as stated in UN (2015). Furthermore, there is an effort to increase the number of countries with risk reduction strategies and availability to early warning systems and to enhance international cooperation. There are 4 priorities in adapting the Sendai Framework which must be adopted at a local, regional, and global level in order to enhance governance strategies, preparedness, and coordination on disasters:

i. Priority 1: Understanding disaster risk
ii. Priority 2: Strengthening disaster risk governance to manage disaster risk
iii. Priority 3: Investing in disaster risk reduction for resilience
iv. Priority 4: Enhancing disaster preparedness for effective response and to 'Build Back Better' in recovery, rehabilitation, and reconstruction

The framework also promotes, especially for developing countries, their cooperation with international stakeholders, such as the World Bank and other international institutions in order to transfer their technological expertise, management techniques, and financial support to successfully achieve the implementation of the measures needed for.

For SDS, the United Nations Economic Commission for Asia and the Pacific (UNESCAP) and Asian and Pacific Centre for the Development of Disaster Information Management (APDIM) have assembled guidelines based on the Sendai Framework. This initiative resulted in a step-by-step guide for the member states to enhance the states' capabilities to monitor and report data from the impacts of SDS and building an evidence base on the negative impacts (UNESCAP-APDIM 2020). Using this framework before any mitigation or adaptation measures could be an effective way of assessing the situation of how well the impacts from SDS are monitored and recorded so that the correct actions can be taken.

8 Conclusions

SDS is a phenomenon that starts locally and can grow globally. As a result, it is of increasing importance, especially in view of climate change, due to the scale of its impacts. To mitigate or adapt the effects of SDS, this critical review examines a wide range of measures and challenges in their implementation. In addition, remarks were made regarding the connection between the EMR and source areas. The main concluding remarks of this review are as follows:

(1) Mitigation measures implemented on a small scale in the source areas did not mitigate SDS on an impactful level. Large-scale implementation measures need to be introduced

to prevent or reduce sand and dust suspension from the source areas, considering the successes and difficulties of the considered measures to be applied, as in the case of the Great Green Wall and Lake Chad Action Plan. The large-scale planning requires substantial funding, especially in the SDS source areas that do not have the national resources to cover the cost of the management techniques in vast areas. This comes down largely to external/international funding such as from the World Bank and the Green Environment Facility. Except financial support in SDS source areas, technical and governance assistance needs to be also provided for the project to be successful monitoring and reporting.

(2) The implementation of adaptation measures focuses on early warning systems using forecasting models. The models require more in situ data from the source areas, and an improved network for sharing information to obtain a more complete picture of the SDS. No other adaptation measures were found to be implemented for the EMR, or whether an extensive network of warnings for employers or businesses from authorities was successfully applied. To our knowledge, a project, the MEDEA project (LIFE + MEDEA 2020), targets its efforts on the feasibility and effectiveness of different adaptation measures for personal protection. The results of this project indicated that with use of technology and personal alerts, target groups were asked to take measures during an SDS event and significantly reduced their exposure to PM pollutants. The adaptation measures must also ensure that all SDS, independent of scale or intensity are considered. This consideration is crucial because the influence of dust (e.g. performance of photovoltaic system, contaminate water bodies) is always persistent, not only when certain political threshold criteria are fulfilled.

(3) Assessing the socio-political-economic situation in each area is critical and must be considered in an overall approach to implementing mitigation and adaptation measures while considering the positive and negative of SDS. Despite their negative impacts, SDS can be crucial drivers of positive global impacts, such as the fertilisation of the Amazon forest. Thus, substantially reducing SDS through a series of measures can damage the environment. Examples that have affected the unsuccessful implementation of measures are the insufficient training of local populations, the lack of common goals in governmental policies, the lack of supervision in the implementation of measures, and a suitable behaviour or perception of a situation. Insecurity and the lack of funds in related projects are also situations found to be important for adopting measures for SDS.

(4) Future pressures are expected to modify the extent of the source areas. Climate change affects differently each area of interest we investigated in this review, and the projections are inconsistent, showing, for example, either increasing or decreasing rainfall. Preventing the further impacts of climate change or stabilising it can help with SDS mitigation and adaptation. Moreover, population increases or social pressures such as poverty or the need for immigration in search of food and security have been shown to affect lands and promote desertification. The ageing population will also be a challenge for competent authorities because they will need to increase their organisation, infrastructure, and protection mechanisms to cope with the potential increase in SDS due to climate change or humanitarian crises. Lastly, shortage of basic resources such as water can result to conflicts between countries and internal instability leading to the abandonment of land and SLWM which can promote SDS, thus affecting areas far away from sources. Thus, tools such as the Sendai Framework for Disaster Risk Reduction are best to be used before adopting measures.

For further research, the socioeconomic and political teleconnections (i.e. an action in an area affecting another area far away) between SDS sources and the EMR can be studied because this connection can result in major SDS. Such a teleconnection can be because the source areas affecting the EMR have been troubled by non-peaceful conflicts, as in the case of Syria, and this can further degrade the lands and drive farmers away, enhancing dust suspension or forming new dust sources.

In closing, the EMR is an area affected by different SDS source areas, each of different social, political, and economic dimensions, necessitating a customised approach for implementing wind erosion mitigation measures. Notably, adaptation measures are mainly based on early warning systems and progress accordingly with capacity building to provide accurate forecasts. For the proper use of accurate forecasts, more infrastructure, organisation, and will from competent authorities and employers to implement adaptation measures are required. The socioeconomic and political context for implementing various mitigation and adaptation measures should always be examined before proceeding. This review can guide policymakers, planners, and engineers to what they should consider before selecting and implementing measures to mitigate or adapt to SDS.

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Data availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication I would like to declare on behalf of my co-authors that the manuscript has been approved by all authors for publication, and the work described is original research that has not been published previously, and is not under consideration for publication elsewhere, in whole or in part. All of the listed authors have approved the enclosed manuscript.

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