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Biomagnetic Studies as a Low-Cost Proxy for Particulate Matter Monitoring in the Arid Desert Region: A Case Study from Western Rajasthan in India

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ABSTRACT

In this study, PM monitoring was performed by biomagnetic analysis of roadside plant leaves of Azadirachta indica A. Juss (neem tree) in the arid desert region of Jodhpur in western Rajasthan, India. This study used the remanent magnetisation of PM10 deposited on neem leaves as a proxy for PM biomonitoring. The saturation isothermal remanent magnetisation (SIRM) showed a strong linear relationship (Pearson's r = 0.9340, p = 0.006) with PM10 data from the low-cost PM sensor. Among six sampling sites, the highest PM10 concentration (88.8 ± 9.8 μg/m³) and SIRM value (7231.2 mA) were observed in the Basni industrial area, confirming the significance of vehicular and industrial emissions. Conversely, the IIT Jodhpur campus, isolated from anthropogenic sources, still exhibited high SIRM values (1904.4 mA), attributed to magnetite-type minerals transported via aeolian processes from the Thar Desert. SEM-EDS analysis further confirmed the presence of crustal minerals (Al, Si) alongside anthropogenic elements (Fe, K, Ca, Mg). A comparative financial study revealed that biomagnetic monitoring (~50,000 INR for ten sites) is significantly more economical than conventional CAAQMS (~110 million INR for ten stations). These findings demonstrate that biomagnetic monitoring offers a robust, low-cost proxy for PM10 mapping in arid desert regions, with strong implications for public health and environmental management.

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INTRODUCTION

A visit to the air quality monitoring portal, https://www.iqair.com/unep, of the United Nation's Environment Programme will reveal that majority of global population is exposed to the ambient air that does not meet the World Health Organization (WHO) air quality guidelines (WHO, 2016; Kinney, 2018). The WHO has reported that approximately seven million premature deaths are caused annually by air pollution, resulting in more cases of illness and hospitalisation. Among air pollutants, particulate matter (PM), categorised into PM_{10}, $PM_{2.5}$, and $PM_{0.1}$ based on the mean aerodynamic diameter, is particularly harmful as microscopic particulates can penetrate deep into the lung tissues and enter the bloodstream, causing oxidative stress and leading to various cardiopulmonary disorders (WHO, 2022). PM monitoring is the

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first step in addressing the challenges of air pollution and creating healthy living zones for the populace. In India, the National Air Quality Monitoring Project, run by the Central Pollution Control Board (CPCB), monitors ambient air quality through a network of 804 stations, including 500 Continuous Ambient Air Quality Monitoring Systems (CAAQMS) that serve 344 cities/towns spread across 28 states and 6 union territories (CPCB, 2020). According to the guidelines set forth by the CPCB, the number of CAAQMS and manual monitoring stations in India is insufficient, which suggests one monitoring station per 25,000 people (CPCB, 2003). Following the guidelines, it is expected to have approximately 4000 – 8600 monitoring stations per million persons, with low and high values accounting for the minimum and maximum monitoring station densities, respectively (Brauer *et al.*, 2019).

As CAAQMS systems are very expensive, it is farfetched to have such a high number of monitoring stations in a large and developing country such as India. Therefore, there is a need to look for alternative low-cost methods that can fill in the gap of low number of monitoring stations so that an accurate spatial representation of the pollutants is available. Low-cost fixed sensors and portable or personal air quality monitors that individuals carry during their commute can help create and develop high-quality air quality maps. Numerous community-driven projects based on crowdsourcing air quality data from low-cost sensors have been reported (Plume Labs, 2017; Brzozowski, Maczyński & Ryguła, 2020; Giordano et al., 2021; Raheja et al., 2022; Westervelt et al., 2024). Biomagnetic monitoring is another alternative for PM monitoring, which uses the principle of the dry deposition of aerosol particles on biological matter (Rai & Chutia, 2016; Hofman et al., 2017). These studies can significantly enhance the prevalence of PM when combined with low cost PM sensors, especially in developing countries, where conventional monitoring methods impose a substantial financial burden. The investment costs for setting up the CAAQMS based on conventional equipment can go up to ten million rupees per station and approximate running costs of five million rupees per year (Brauer *et al.*, 2019; Pant *et al.*, 2019). Therefore, there is a need to explore alternative low-cost air pollution monitoring methods, such as biomagnetic monitoring. Biomonitoring can be viewed as a quantitative (biomonitor) and qualitative (bioindicator) approach to gauge pollution levels. Sampling is simple and straightforward, allowing for the analysis of regional and temporal variations in PM. The main underlying principle of biomagnetic monitoring is the presence of magnetic material in PM, which has been proven in numerous studies (Moreno et al., 2003; Mitchell & Maher, 2009; Rai, Chutia & Patil, 2014; Hofman et al., 2017; Paoli et al., 2017; Gillooly et al., 2019; Sheikh et al., 2022).

When a non-volatile residue, generally a mix of highly magnetic (such as magnetite) and slightly magnetic (such as haematite) iron oxides, is deposited on the leaves of the plants, they are trapped on the leaf surface until some physiological changes occur, such as high wind conditions or rain. Magnetite is found in urban PM from anthropogenic sources such as combustion, construction, mining, automobile exhaust, and non-exhaust emissions (Maher, Moore & Matzka, 2008; Kawasaki, Horikawa & Sakai, 2017; Rai et al., 2020). Road traffic and construction activities are recognised as primary sources of urban air pollution; therefore, biomonitoring of roadside tree leaves typically reveals the quantum of PM pollution in the vicinity of the trees, although other sources may also be present, depending on the geology of a given environment. There are well-known, albeit relatively few, biomagnetic studies on PM in the arid regions of Africa (Dawaï et al., 2021; Jeddi et al., 2021), the Middle East (Al-Shayeb, Al-Rajhi & Seaward, 1995; Lavi et al., 2016; Norouzi et al., 2016; Khamesi, Khademi & Zeraatpisheh, 2020), and Asia (Rai, 2015; Sheikh et al., 2022); however, we believe that this study is the first of its kind in the arid desert region of northwestern India. In this study, measurements from both low-cost personal sensors and biomagnetic studies in the arid desert region of western Rajasthan, India, were used as a case study to monitor PM_{10} and present the cost implications of different methods for PM monitoring.

MATERIALS AND METHODS

Jodhpur (27.62°N 72.92°E - 26.00°N 73.87°E) is the second largest metropolitan city located in the western region of Rajasthan province and falls under the arid hot desert (BWh) region according to the Köppen climate classification. Jodhpur city has an area of approximately 233 km^2 and has a population of 1,138,000 as per the 2011 census, and the population in 2021 is 2,330,000 as per estimates (Jodhpur Development Authority, 2016). The six sampling sites chosen for this study are shown in Figure 1 and are listed below.

Site 1: *Indian Institute of Technology Jodhpur (IITJ) Campus:* The IIT Jodhpur campus is an educational institute and was selected as a reference site because traffic-related emissions are minimal, and any dust deposited on the leaves is due to the typical dust storms in a desert region. The campus is located 25 km away from the Jodhpur city.

Site 2: *Nehru Park:* This site is a public park located in a residential area with light to moderate traffic.

Site 3: *Shastri Nagar Circle:* This site is located south of Jodhpur city and has moderate to heavy traffic density.

Site 4: *Collectorate Office:* The Collectorate Office is surrounded by arterial roads with moderate to heavy road traffic, and one of the four CAAQMS monitoring stations in the Jodhpur region is located at this site.

Site 5: *Jalori Gate:* This sampling site was chosen because it is the busiest road junction in the city, with very high traffic density.

Site 6: *Basni:* This site is located in an industrial area with a high density of commercial vehicles, resulting in heavy traffic.

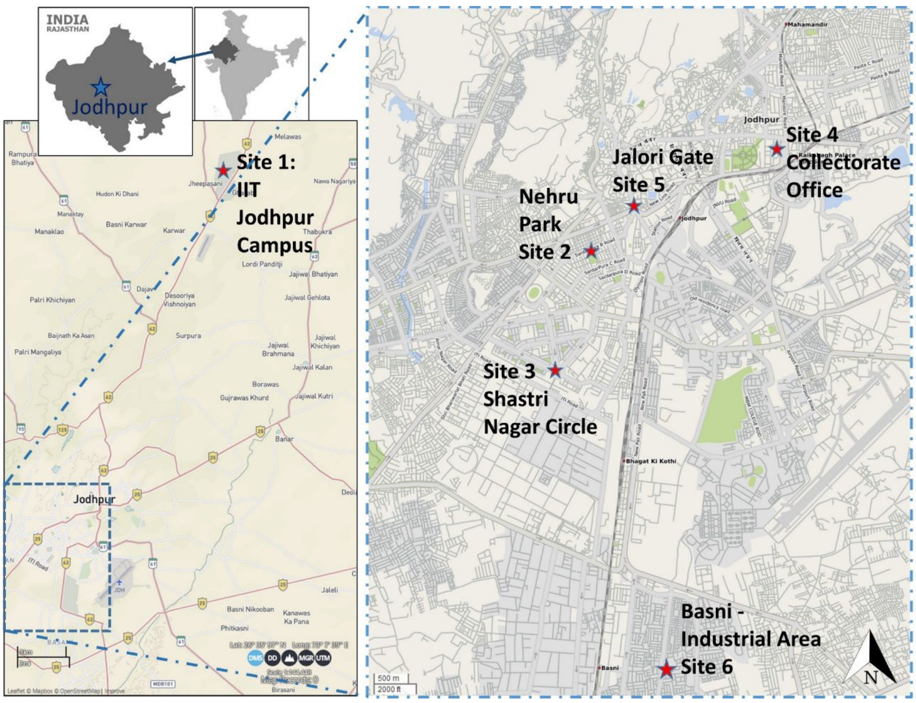

Fig. 1. Sampling sites chosen for this study.

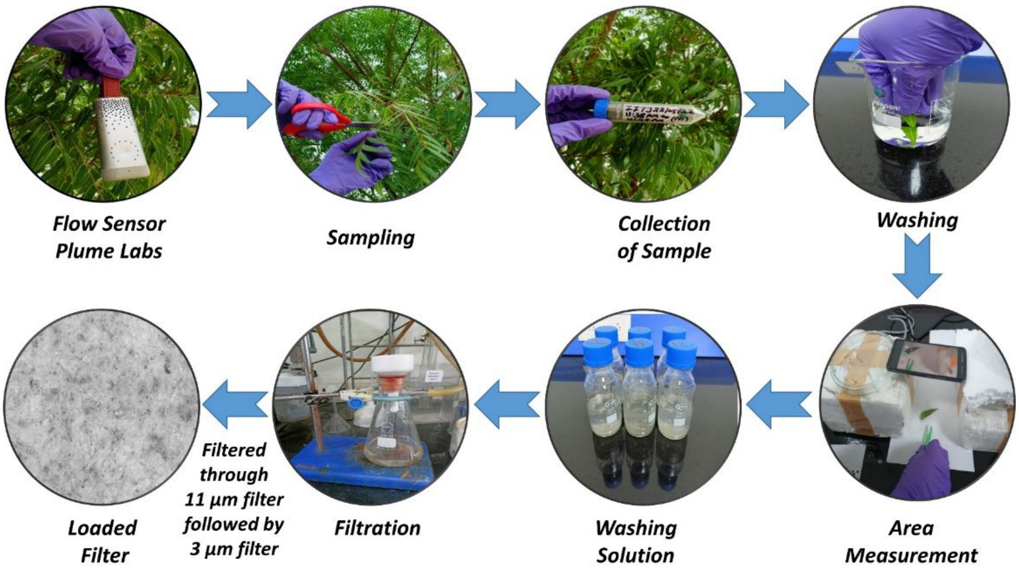

Fig. 2. Schematic diagram of sampling, washing and filtration steps

Sampling was performed in summer at the six sampling sites spread over three days at similar times in the forenoon, that is, 08:00–12:00 h, while considering that there was no rainfall at least five days prior to the sampling. Neem (*Azadirachta indica A. Juss*), an evergreen plant species, was chosen as the ideal plant for sampling because of its availability throughout the city of Jodhpur. Neem leaves fall under the compounded leaf category and are petiolated, showing a dark glossy green at maturity, 20-40 cm in length, and each mature leaf bears 10-20 leaflets. Leaves were picked from the trees close to the roadside at a height of approximately two meters, which represents the breathable air plume height levels and prevents contamination from soil splash. Leaves of comparable size from branches facing the roadside were collected in 50 ml centrifuge tubes and transported to the laboratory for further experiments. At the same time, a handheld air quality sensor *Flow* developed by Plume Labs (Plume Labs, 2014) was used to measure the PM_{10} concentrations at each of the sampling sites, and the sensor measurements were taken for at least 10 minutes. Sensor data were cross-validated against the Continuous Ambient Air Quality Monitoring Station (CAAQMS) at the Collectorate Office, with deviations within ±10% (Table S1, supplementary file). It should be noted that *Flow* is no longer available in the market as it has been replaced with *Flow 2* by Plume Labs. The leaf samples were brought back to the laboratory and washed with Milli-Q water (resistivity >18 MΩ). The washed solutions were initially filtered using 11 µm pore size polycarbonate membrane filters (Cyclopore Whatman), and the collected filtrate was passed through 3 µm and 0.25 µm pore size filters in a sequential step. After filtration, the entrapped PM on the filter membranes was allowed to air dry at ambient temperature in a desiccator before being sent for magnetic analysis to the Birbal Sahni Institute of Palaeosciences (BSIP) in Lucknow, India. The surface area of the leaves was measured using the *PetiolePro* app (PetiolePro, 2023) to normalize the magnetic parameters.

SEM and optical microscope images of the leaves and filter membranes were obtained before and after the washing steps. The schematic of the sampling procedure is shown in Figure 2 and is similar to that of previous studies (Matzka & Maher, 1999; Hofman et al., 2014, 2017). A Carl Zeiss EVO 18 SEM coupled with EDS (Oxford Instruments) was used for the electron micrograph images and elemental characterization of the PM deposited on the filters.

A Leica DM6 M upright microscope fitted with LED illumination was used to analyse the filter membranes before and after filtration. An impulse magnetizer (Model IM-10-30; ASC Scientific) was used to impart magnetization to the samples. Progressive forward acquisition of the remanent magnetization was performed from 20 mT to 1000 mT in seven intermediate steps. The remanent magnetization obtained at the 1000 mT pulse field is considered the saturation isothermal remanent magnetization (SIRM). Progressive backfield demagnetization of the SIRM was performed from 20 mT to 300 mT in six intermediate steps. A JR-6 dual-speed spinner magnetometer (AGICO) was used to measure the remanent magnetization at each acquisition and demagnetization step in the high-speed mode. The S-ratio was computed to measure the relative concentration of soft and hard magnetic minerals in the PM by calculating the ratio of the absolute value of IRM at -300 mT over SIRM, i.e., $|IRM_{-300mT}|/SIRM_{1000mT}$.

RESULTS AND DISCUSSIONS

There are numerous species of trees in arid regions; therefore, selecting the type of species for the study is dependent on various factors, primarily the availability of the tree species across the study area, the height of the tree in all the sampling sites, climate, and location. Evergreen trees are better particle trappers than deciduous trees because their leaves have a longer lifespan and can store pollutants year-round. Therefore, the evergreen species *Azadirachta indica A. Juss.*, i.e., neem, was selected for this study which suited all the requirements. The PM_{10} measurements (Table 1) from the handheld air quality sensor *Flow,* showed that Site 6 (Basni) has the highest PM_{10} concentration at 88.8 ± 9.8 μg/m^3 which is due to the industrial activity and heavy road traffic. Site 3 (Jalori Gate) had the second highest PM_{10} level of 72.7 ± 5.5 μg/m^3, and this is because of extremely heavy concentration of vehicular traffic as this is the most busiest road junction in the Jodhpur city. The PM_{10} concentrations at Site 2 and Site 5, i.e., Collectorate Office and Shastri Nagar Circle, were found to have values of 66.2 ± 8.8 μg/m^3 and 63.8 ± 8.6 μg/m^3, respectively. Both the locations have moderate to heavy traffic density as Site 2 is surrounded by arterial roads connecting different parts of the city from the city bus station that is located opposite the Collectorate Office, and Site 5 is surrounded by shopping streets, hospitals, eateries with moderate to heavy traffic round the clock. In comparison, Site 4, i.e., Nehru Park, which is an urban city park located in a residential area, has a PM_{10} concentration of 60.1 ± 7.5 μg/m^3, whereas the lowest value of PM_{10} concentration was recorded at the IITJ campus with a value of 50.2 ± 6.8 μg/m^3. This information is also shown in the form of an AQI hotspot map available in the Plume Labs smartphone app, tracked with the connected GPS feature of the sensor providing real-time air quality data.

The Flow sensor was compared with the data from the CAAQMS station located at the Jodhpur Collectorate Office, which is one of the four CAAQMS stations in the Jodhpur region, and the deviation in the data was found to be within ±10% (Table S1, Supplementary file). The magnetic parameters, i.e., soft isothermal remanent magnetization (Soft-IRM), hard isothermal remanent magnetization (Hard-IRM) and SIRM of the samples were normalized with the cumulative surface area of the leaves at the specific sampling site. From the magnetic parametric data, tabulated in Table 1, it can be observed that the S-ratio at all the sampling sites is higher than 0.95 and this points towards the high proportion of low-coercive ferrimagnetic nature of PM at all the sampling sites which is also reflected in the Soft-IRM values. A high value (~ 1) of S-ratio indicates the presence of predominant ferrimagnetic particles, whereas lower S-ratio values refer to the presence of mixing mineralogy of magnetite and anti-ferromagnetic minerals haematite and goethite in the samples (Bates, 2002; Liu *et al.*, 2007). The Soft-IRM data presented in Figure 3 indicates the increasing magnitude of magnetite-type minerals attributed to higher pollution levels primarily due to emissions from anthropogenic activities such as vehicular and industrial emissions (Moreno et al., 2003; Mitchell & Maher, 2009; Rai & Chutia, 2016; Hofman et al., 2017; Paoli et al., 2017; Larrasoaña et al., 2021). Site 1: IITJ Campus, which is located 25 km away from the city and devoid of industrial or vehicular emissions, serves as a reference for the evaluation of anthropogenic sources of PM in Jodhpur city. But, from Figure 3, we can observe that Site 1, with almost non-existent anthropogenic sources of PM emissions, also has significant amounts of low-coercive ferrimagnetic minerals in the form of high S-ratio = 0.97, SIRM and Soft-IRM values.

The SEM-EDS analysis (Figure 4) of the loaded filter sample from Site 1 consisted of only the elements Al and Si in the form of silica and alumina, which are the typical Thar desert minerals (Yadav and Rajamani, 2004; Padmakumar *et al.*, 2012). In fact, SEM-EDS of all the samples as seen from Figure 4 indicated the presence of Al and Si, and increasing amounts of other elements, i.e., Fe, K, Ca, and Mg, were detected corroborating the previous PM monitoring studies which attribute these elements to vehicular and industrial emissions (Mathur & Choudhary, 1997; Sagnotti et al., 2009; Agnihotri et al., 2020; Roy, Habib & Raman, 2024). Consequently, we conclude that the presence of magnetite minerals in the leaf-deposited PM in Site 1, which is shielded from anthropogenic sources of PM, could only be due to the PM

Table 1. Magnetic parameters and low-cost PM10 sensor measurements

Sampling Site	PM_{10} (μg/m^3)	Normalized SIRM (mA)	Normalized Soft-IRM (mA)	Normalized Hard-IRM (mA)	S-ratio
Site 1: IITJ Campus	50.2 ± 6.8	1904.4 ± 47.2	1746.0 ± 87.3	64.6 ± 9.1	0.97 ± 0.01
Site 2: Nehru Park	60.1 ± 7.5	2487.3 ± 69.0	2335.0 ± 46.7	78.2 ± 6.8	0.97 ± 0.01
Site 3: Shastri Nagar Circle	63.8 ± 8.6	2589.3 ± 52.9	2368.5 ± 71.1	108.9 ± 13.8	0.96 ± 0.01
Site 4: Collectorate Office	66.2 ± 8.8	3217.1 ± 71.1	3101.1 ± 46.5	173.6 ± 16.0	0.95 ± 0.01
Site 5: Jalori Gate	72.7 ± 5.5	3682.6 ± 63.3	3193.0 ± 63.9	105.5 ± 19.5	0.97 ± 0.01
Site 6: Basni	88.8 ± 9.8	7231.2 ± 153.9	6505.6 ± 292.8	367.5 ± 36.5	0.95 ± 0.01

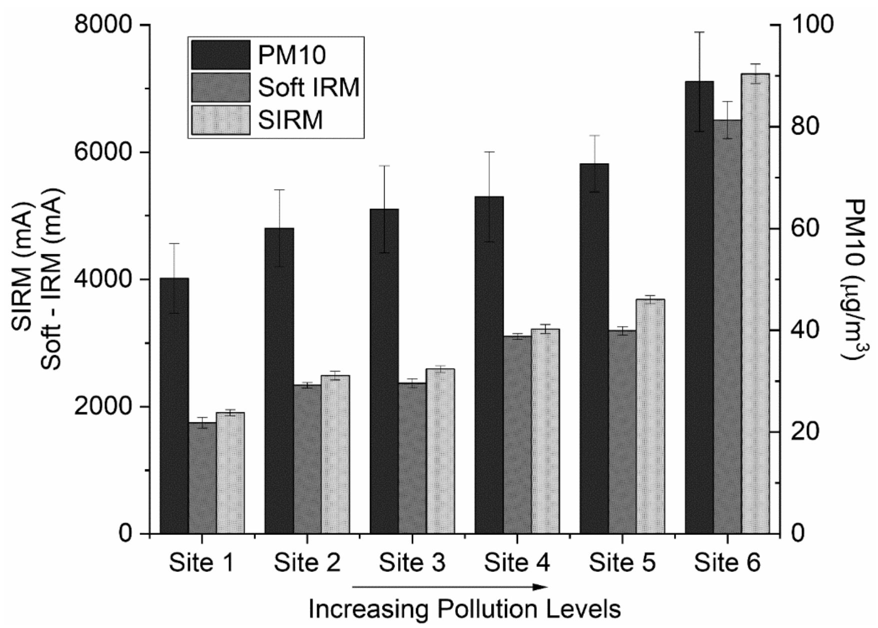

Fig. 3. The PM10 measurements comparison with the normalized values of SIRM and Soft-IRM. The sampling sites are ordered as per the apparent PM pollution levels in Jodhpur city.

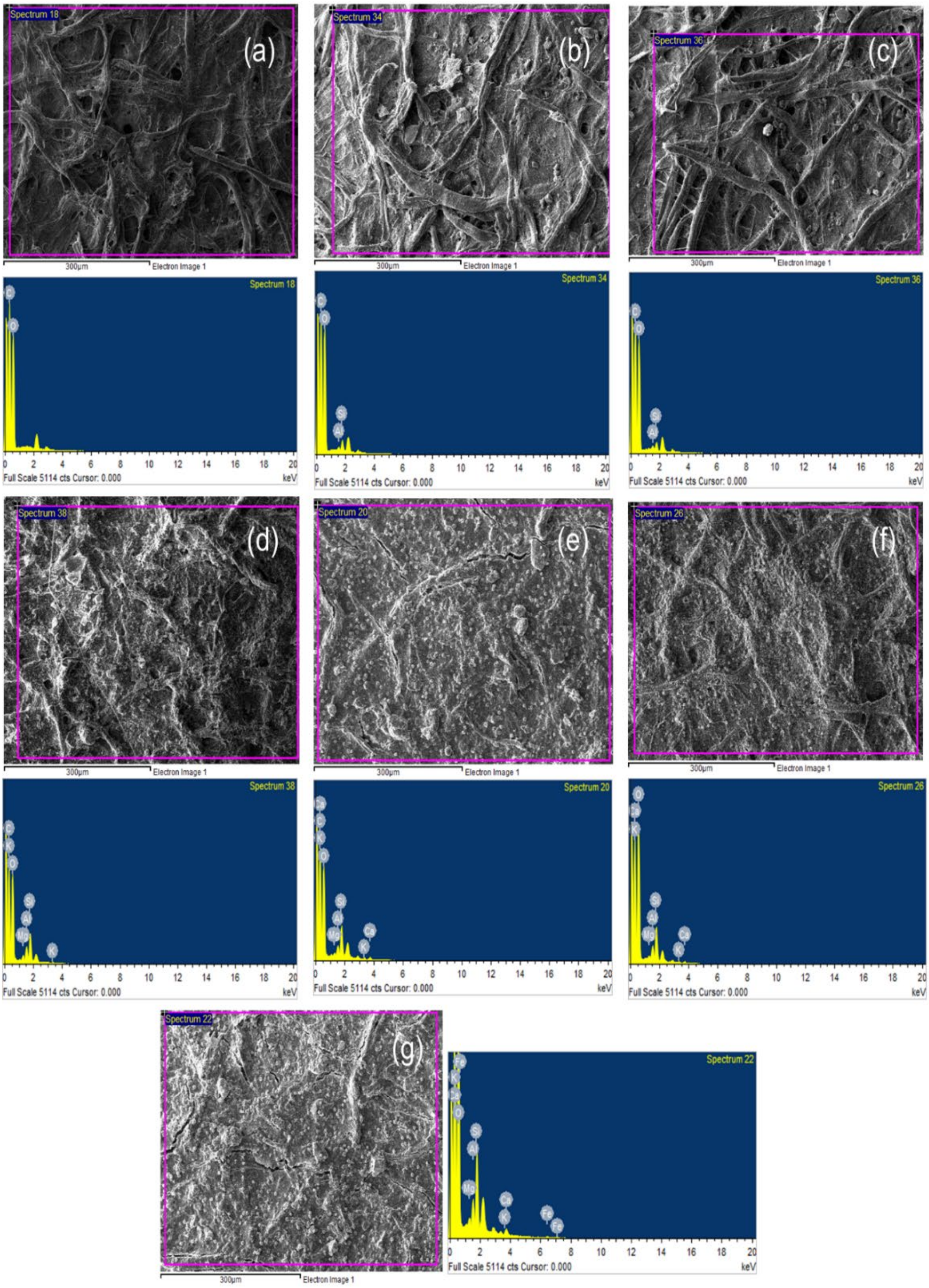

Fig. 4. SEM-EDS analysis of (a) blank filter and loaded filters of samples from (b) Site 1: IITJ Campus (c) Site 2: Nehru Park (d) Site 3: Collectorate Office (e) Site 4: Shastri Nagar Circle (f) Site 5: Jalori Gate and (g) Site 6: Basni. The scale bar at the bottom right corner of all the micrograph images is 300 µm.

transported through aeolian process from the Thar desert region located in the close vicinity of Jodhpur in western India. Additionally, the optical microscopic images (Figure S1) of the dried filter samples from Site 1 also revealed particulate matter trapped on the filter papers during the washing step. Source appropriation studies carried out in the desert region of western Rajasthan have revealed that there several factors for such high levels of PM. They are primarily due to the high frequency of dust storms that result in resuspension of aerosol particles from the crustal sources (Sagnotti et al., 2006; Roy, Habib & Raman, 2024) and from the large number of sandstone quarries surrounding the Jodhpur region (Mathur & Choudhary, 1997; Agnihotri et al., 2020). Similar observations were made in prior studies such as the presence of hematite, originating from Sahara Desert and transported to western and south Europe through the aeolian process (Larrasoaña *et al.*, 2021).

SIRM provides information on the concentration of ferrimagnetic grain particles, which can directly be used as a PM proxy, and numerous studies have shown strong correlations between SIRM and PM concentrations (Moreno et al., 2003; Mitchell & Maher, 2009; Lavi et al., 2016; Khamesi, Khademi & Zeraatpisheh, 2020; Sheikh et al., 2022). In this study, the increase in SIRM values with the corresponding increase in PM_{10} concentrations in the sampling sites, as observed in Figure 3, corroborates the claim that SIRM values can be used as a proxy for PM_{10}. The direct relationship between SIRM and PM_{10} levels is clearly reflected in Figure 5, with statistical analysis revealing a strong linear correlation between the normalized SIRM and PM_{10} concentrations ($r = 0.9340$, $R^2 = 0.8724$, $p = 0.006$), with approximately 87% of the variance. Additionally, ANOVA of SIRM data confirmed significant site-wise differences ($F = 9.72$, $p = 0.012$), with Basni and Jalori Gate showing statistically higher PM_{10} and SIRM values than residential zones. Notably, the IITJ Campus, despite its low PM_{10} levels, displayed anomalously high SIRM values (1904.4 mA), which were statistically different from those of other low-traffic sites (t-test, $p < 0.01$). This anomaly may be attributed to the aeolian dust transport. Chi-square analysis of SEM-EDS data (Figure 4) indicated significant enrichment of Fe, Ca, K, and Mg in industrial/traffic sites compared to crustal Al–Si dominance at IITJ Campus. The Pollution Load Index (PLI) (Tomlinson et al., 1980) was calculated using the IITJ Campus as the reference site and is plotted in Figure 6. For all sites, the PLI estimated from PM_{10} concentrations was higher

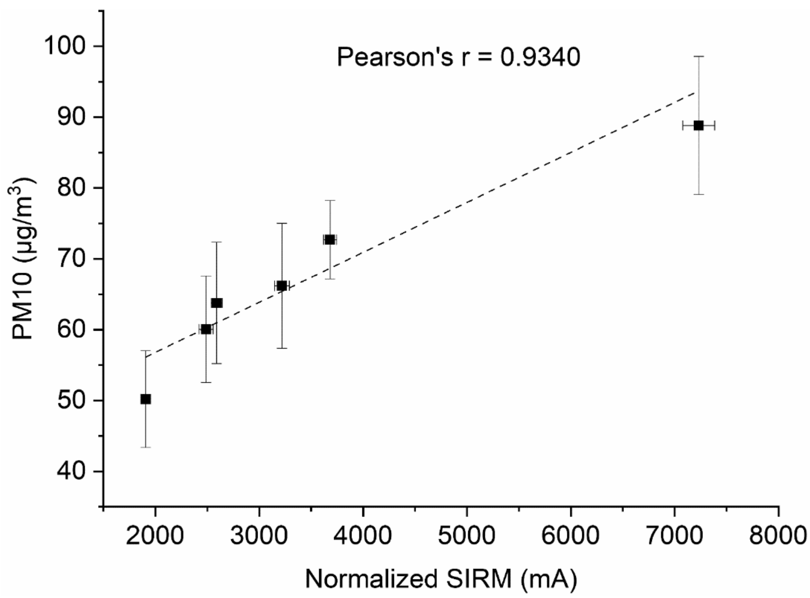

Fig. 5. Correlation between PM10 and normalized SIRM values.

than that based on SIRM values, suggesting a greater pollution load when magnetic proxies were employed. Site 6 (Basni) exhibited a disproportionately high contribution, with contamination factors nearly four times the baseline. These findings statistically validate that biomagnetic monitoring not only reflects particulate matter concentrations but also highlights anthropogenic contributions to urban pollution loads. The high PM levels due to traffic or industrial activity are also shown in Figure 3, where the PM_{10} measurements, Soft IRM and SIRM values show a direct relationship with increasing pollution levels. Site 1 is located inside the campus of IIT Jodhpur, which is an institutional area with an extremely low density of traffic and is found to have the lowest values of SIRM and Soft IRM among all sites. This is also supported by the moderate PM_{10} measurement of 50.2 ± 6.8 μg/m^3 measured by the low-cost PM sensor at Site 1, as shown in Table 1 and Figure 3. The most polluted location among all the sampling sites, i.e., site 6, is located in the Basni Industrial area, where both traffic-derived emissions and industrial emissions contribute to the high SIRM and Soft-IRM values, as it is well-known that traffic and industrial emissions contain ferrimagnetic magnetite minerals released during the combustion processes (Maher, 2009; Sagnotti *et al.*, 2009; Rai and Chutia, 2016; Sheikh *et al.*, 2022).

However there are some exceptional studies which have provided an inverse relationship between magnetic properties and PM_{10} data during the Covid-19 lockdown (Winkler *et al.*, 2021) and smoggy winter conditions (Petrovský *et al.*, 2020). Also, it is important to take note that in the absence of rainfall, windstorms and other meteorological events, it is always evident that biomagnetic analysis reveals PM nature of accumulated particulates over a long term, and the PM concentration values, measured from low-cost sensors cannot be confused with bioaccumulation data. Similar approach to analyze $PM_{2.5}$ was not successful as the washing step did not remove all the smaller sized $PM_{2.5}$ from the leaf pores. The SEM analysis and the combined remnant magnetization of leaf samples along with $PM_{2.5}$ retained on filter paper did not provide any meaningful data. Further work is in progress to streamline the washing and magnetization processes for both PM_{10} and $PM_{2.5}$. The motivation for this study stems from the potential of biomonitoring to meet the growing need for low-cost PM monitoring and to develop denser pollution hotspot maps, especially in arid regions. Although biomagnetic monitoring is an established method, its application in the arid desert region of northwestern

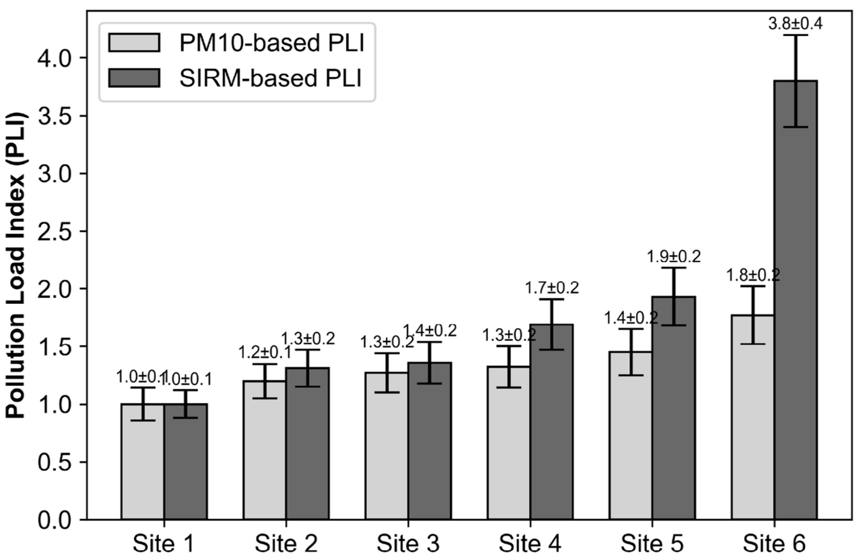

Fig. 6. Pollution Load Index (PLI) calculated from the SIRM and sensor-measured PM10 values across all the sites. Site 1 is used as the reference in this study.

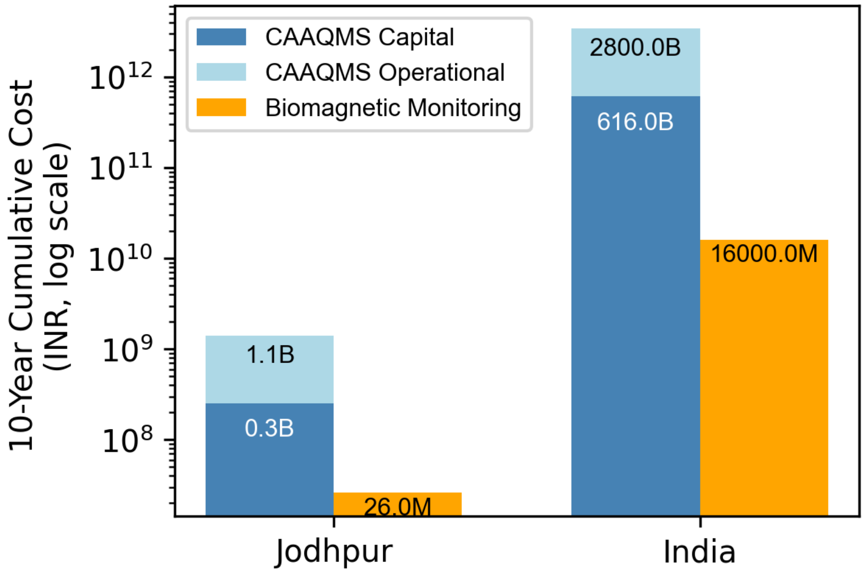

Fig. 7. A 10-year comparative costs of biomagnetic monitoring vs India for Jodhpur and India on a weekly sampling basis.

India is novel. The unique environmental conditions of this region, such as wind-driven PM deposition from the Thar Desert, provide a distinct context for investigating biomagnetic techniques for PM monitoring in this region. However, the overall magnetic data indicates that biomagnetic monitoring could be a very good proxy for PM_{10}, even in an arid desert region, which is the basis of this work's case study, and this is the first-of-a-kind biomagnetic study performed in an arid desert (BWh) region in Northwest India. Since the climatic conditions in Jodhpur do not allow evergreen species to thrive naturally, this study would not have been possible without the city administration's effort over decades to plant a significant number of neem (*Azadirachta indica A. Juss*) trees throughout the city. To develop dense air quality data as per the CPCB requirement of a minimum monitoring density of four CAAQMS stations per 100,000 population (CPCB, 2003), a total of 23 stations would be required for Jodhpur city alone as per current city population estimates of 2,330,000 (Jodhpur Development Authority, 2016). Even a hypothetical scenario of establishing only ten CAAQMS stations in hot spot zones would require a total cost of ~ 110 million Indian Rupees (INR), considering the approximate cost of setting up a single CAAQMS station to be around 11 million INR (capital + maintenance costs) in addition to operational costs of 5,000,000 INR in a year (Brauer *et al.*, 2019; Pant *et al.*, 2019). This is very expensive compared with biomagnetic monitoring, with a total cost of ~50,000 INR for ten sampling sites in a day, including ~10,000 INR for magnetic analysis performed at an established lab (BSIP) and ~ 40,000 INR for consumables and workforce.

Figure 7 shows the financial advantages of biomagentic monitoring over a period of ten years, with weekly sampling and extrapolated to country level requirements in India. The estimates are based on the cost analysis for this study. However, it should be noted that biomagnetic monitoring would only provide indirect information on PM levels with no real-time data. There are also some disadvantages of biomonitoring as it cannot provide any information about other gaseous air pollutants such as NOx, SOx, VOCs etc. Also, it is noteworthy to understand that low-cost measurements have some reliability issues and the difficulty of obtaining accurate data from low-cost sensors is a key challenge as observed in some studies where low-cost PM sensors were compared with conventional instruments (Wang *et al.*, 2015; Cavaliere *et al.*, 2018; Feenstra *et al.*, 2019). Nevertheless, biomagnetic monitoring can be an excellent low-cost alternative for long-term studies to develop dense spatial resolution of PM levels across a city, with intermittent sampling spread over different seasons, and will be more economical for developing countries with no CAAQMS infrastructure in place.

CONCLUSIONS

A strong linear correlation (r = 0.9340, p-value 0.006) between PM_{10} data measured from a low-cost sensor and SIRM was established in this case study in an arid desert region. The statistical findings corroborate that biomagnetic monitoring is sensitive to both anthropogenic and aeolian sources, offering a robust low-cost proxy for PM_{10} mapping. The highest magnetic parameter values of SIRM and Soft-IRM were found for the sampling site located in the industrial area. The low-cost PM sensor data, SIRM and Soft-IRM data follow a pattern of increased concentration levels with corresponding higher levels of PM pollution. For every 1000 mA increase in SIRM, PM_{10} rises by ~11 µg/m³, confirming biomagnetic monitoring as a quantitative proxy. The sources for the low-coercivity magnetite-type minerals at all sampling sites are vehicular and industrial emissions, causing varied amounts of PM_{10} deposited on roadside tree leaves. However, for the only sampling site isolated from vehicular and industrial emissions, the aeolian process from the Thar desert region is responsible for intense values of magnetic parameters. In brief, using the fundamental basis of leaf magnetic measurements as a proxy for PM_{10} offers a higher spatial resolution and feasible cost-effectiveness which is already well reported in detail in numerous other studies and such an approach has yet to be used in the distinctive arid location represented by Jodhpur. And this study shows that biomagnetic monitoring can be an excellent tool for case studies involving large numbers of sampling sites, even in an arid desert region. Biomagnetic monitoring has shown great promise worldwide in meeting the rising demand for cost-effective approaches to record air pollution at high spatial resolution with significant environmental and public health implications. Importantly, biomagnetic monitoring proved to be orders of magnitude more cost-effective than conventional CAAQMS, enabling denser spatial coverage in resource-limited settings.

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DECLARATIONS

The corresponding author (Ramesh Asapu) is currently not associated with IIT Jodhpur, but the work was done during his association with the institution.

GRANT SUPPORT

The financial support for this study was provided by IIT Jodhpur.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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