Prominence Study of Pill-Millipedes of the Genus Arthrosphaera (Diplopoda: Sphaerotheriida) in Diverse Plantation and Semi-Evergreen Forest of Satara, Western Ghat, Maharashtra

Shaikh N. A.[*], Abdar M. R., Kamble K. J.

1. [*]Research student, Y.C. College of Science, Karad, Satara, Maharashtra, India
2. Dept. of Zoology, Krantisinh Nana Patil College, Walwa, Sangli, Maharashtra, India
3. Dept. of Zoology, D. P. Bhosale College, Koregaon, Satara, Maharashtra, India

ABSTRACT: To conserve the study and protection of ecological organizations, it is important to understand the variety of pill-millipede species that surround specific areas. The main aim of examining the habitat taxonomies in areas like the forest is to identify the species of pill-millipede and their distribution. They belong to the class Diplopoda of the phylum Arthropoda, and their segmented body is typically associated with their habit of digging in soil. The present study in Satara, Western Ghat, Maharashtra focuses on the variety, distribution, and conservation of pill millipedes. The pill-millipedes belonging to the genus Arthrosphaera have a long history in the Indian subcontinent and have been increasing in number. In India, 40 species of Arthrosphaera have been documented. In the current study, we found a large number of *Arthrosphaera carinata, A. distcta Pocock, A. fumosa Pocock,* and *A. magna Attems* species out of the 4 species of the genus Arthrosphaera. These species were detected in morning and evening periods at wet places under foliage litter from January 2023 to December 2023. Their abundance was higher in the plantation zone compared to the plantation itself due to the presence of rich biological material. This genus can protect rotten foliage litter by converting it into organic manure in the form of faecal pellets. The presence of pill millipedes contributes to the overall health of the soil. Previous morphological studies on Arthrosphaera were conducted in the 1890s, highlighting the need for a review of their fragmented systematics (Wesener *et al*., 2010). Pill millipedes in India are experiencing a decrease in population due to human interference, particularly in land variation and current forestry, farming practices. It is essential to inform about their status, occurrence, and distribution in different environmental situations as they play a significant role in organic matter decay and nutrient turnover in forests and plantations. A recent study in the Western Ghats of Satara aimed to identify four species of pill millipedes through a diagnostic key. The study also surveyed the seasonal periodicity of pill millipedes in mixed plantations and semi-evergreen to evergreen forests in the Western Ghats, finding that they are restricted to the monsoon and post-monsoon seasons. In plantation and high-altitude forests between monsoon and post-monsoon, soil temperature and pH changed significantly among monsoon and post-monsoon periods in all habitats. The pill-millipedes (Arthrosphaera) were the most prominent extra-large diverse soil fauna observed. Pill millipedes play a crucial role in nutrient cycling by consuming decomposable organic matter. The recent study provides data on the occurrence, distribution, and morphological characteristics of 4 species of Arthrosphaera in the Western Ghats through an investigative key.

Keywords: Arthrosphaera, Conservation, Diversity, Pill-Millipede, Satatra, Western Ghat.

1.0 Introduction

The biological diversity enriches the soil, keeping the water and climatic cycle and changing waste materials into rich compost. Macro invertebrates play an important role in providing richness to soil by stimulating the stability and efficiency of forest monitoring biodiversity in forest ecosystems is an important stage to measuring their functions and providing the essential information for effective management. Invertebrate animals are important, effective components and valuable indicators of other essential elements of biodiversity, conserving of ecosystem and regeneration, fitness structure, and connected threats. While, the most biological importance of invertebrates in forest ecosystems, they have little attention because of identification difficulty. For planning the conservation of these animals, monitoring biodiversity is an important process to determine the diversity arrangement and distribution of species within the plantation ecology. Macro invertebrates enhance the value of forest soil through a breakdown of litter due to nourishing and digging activity. In this significant soil element, millipedes are one of the energetic macro arthropods that contribute to preserving the forest environment. Pill millipedes belong to the genus Arthrosphaera and are large-bodied hollow of venom glands that roll up into an entire ball differ from a marble up to a baseball presenting island gigantism (e.g. Madagascar) (Wesener et al., 2010). Although they are endemic to the tropics and distributed in extensively divided geographic regions of South Africa, Madagascar, India, Australia, and New Zealand, later they were spread off in the transitional regions due to unsuitable climatic environments (Pocock, 1892, 1899; Wesener et al., 2010). The Pill-Millipedes roll into a sphere or Pill (conglobation) as protection activities (e.g. Sphaerotheriidae, Glomeridae). Pill millipedes are vital in organic matter reprocessing in an extensive variability of habitats by mechanical fragmentation and removal of faecal pellets, which grow the surface area for bacterial and fungal colonization (Hopkin and Read, 1992).

2. Literature Review

Pill millipedes are one of the most attractive groups of diplopods due to their giant size, colour, and characteristic conglobation into a ball (or pill) as a protection mechanism (Wesener and van den Spiegel 2009). Glomerida and Sphaerotheriida are the two major orders of pill millipedes dispersed in geologically cold regions in moderate and humid parts of the world, respectively (Wesener et al. 2010). The order Sphaerotheriida covers the three major zoogeographic regions Oriental, Ethiopian, and Australia (Pocock 1899, Attems 1936, Wesener et al. 2010).

Recently some studies have been carried out on the occurrence, distribution, daytime periodicity, morphology, cytology, the impact of soil edaphic factors, leaf litter preference, organic matter processing and gut bacteria of Arthrosphaera of the Western Ghats (e.g. Ashwini and Sridhar, 2005, 2006a, 2006b, 2006c; Kadamannaya and Sridhar, 2009a, 2009b; Kadamannaya et al., 2010a, 2010b; Kämpfer et al., 2011). Studies on pill millipedes of the Western Ghats are stimulating as they are conservative and largely habitat-dependent (e.g. soil, forest floor and climatic features) and essential exact edaphic situations. The present paper applications detail the recent information on the distribution, ecosystem, bioconversion, systematics, and protection of Arthrosphaera in in the Western Ghats of Satara.

There are numerous gaps in our knowledge of Pill millipedes. Their occurrence of an exact place represents developed soil abilities. Pill millipedes serve as good candidates for Nourishment manufacture by decomposable solid wastes. Soil humification is an important procedure carried out by the saprophagous fauna in forests and plantations. Pill millipedes among saprophagous macrofauna are important in soil humification. Organically managed mixed plantations of the southwest part of Satara resulted in high diversity and activity of many saprophagous fauna. Among the pill millipedes *Arthrosphaera magna* Attems become abundant in organically managed mixed plantations. Pill millipedes were never found or colonized in the chemically managed plantations. However, they were common in semi-evergreen forests adjacent to mixed plantations. Therefore, the major objective of the present study was to extend the investigation on the seasonal occurrence of pill millipedes found in mixed plantation forests of the Western Ghats at different altitudinal ranges about the soil edaphic features.

Many of the morphological terms in pill millipedes are indefinite and incompetently described (Wesener & Sierwald, 2005b). The sexual structures are important and they are likely species-specific, but they were not described. Anterior and posterior telopods with exact features have a prominent character in separating species. The anterior telopods with stridulation ribs mainly on the first podomere are extremely characteristic. Two stridulation ribs are seen in *Arthrosphaera dalyi, A. fumosa,* and *A. magna,* while it was signified by a single rib in *A. disticta*. Comparisons of detailed morphological structures of four Arthrosphaera spp. studied are given in Table 1. The ribs play the main role in stridulation, which leads to the breeding arrangement (Wesener et al., 2011). The number of ribs differs between species and the aging of individuals plays an important role in absorbing the complete structure of ribs (Wesener & Sierwald, 2005a).

Despite large diversity and distribution in distinct ecological conditions, Arthrosphaera was severely under-documented and evolutionary significance is less known (Kadamannaya and Sridhar 2009; Kadamannaya et al. 2012; Ambarish and Sridhar 2013). The Indian subcontinent was part of Gondwana land and the sister taxon of the genus Sphaeromimus was reported recently from Madagascar (Wesener et al. 2010). The Western Ghats of India being a major hot spot of biodiversity, innumerable number soil fauna including giant pill millipedes need specific attention.

Historically, the myriapodological exploration dates back to the 1890s with documentation of about 27 species of pill millipedes belonging to the genus Arthrosphaera from the Indian subcontinent till the mid-1930s (Pocock 1895; Attems 1936). Amazingly, up to 70 years (till the early 2000s), the systematics of Arthrosphaera was undamaged. During 1960–87, most of the studies were concentrated on the cytogenetics (e.g. Chowdaiah 1962, 1966a, b, c; Chowdaiah and Kanaka 1974; Achar 1980, 1986, 1987). Newly, Ashwini (2003) has recognized three species of Arthrosphaera and highlighted their ecosystem and scavenging approaches. Later, Kadamannaya (2008) reinitiated systematics and explanation of Arthrosphaera through documentation of eight extra species from many environmental situations of the Western Ghats followed by Ambarish (2014). Due to major inadequacies in the systematics of the genus Arthrosphaera in the Indian subcontinent and to stimulate further investigation, the present study provides information on the occurrence, distribution, and morphological description of four species of Arthrosphaera in the Western Ghats with a diagnostic key based-on light as well as scanning electron microscopy.

Giant pill millipedes belonging to Sphaerotheriida are one of the most conspicuous invertebrates in the forest ecosystem of the Western Ghats (Ashwini & Sridhar, 2008). However, the pill millipedes are extremely ignored soil fauna in several features of their morphology, cytology, and diversity (Wesener et al., 2010).

To the determined amount of my information, no reports reside describing the terrestrial distribution construction, variety, and community structure of Pill millipedes. Only limited data have been available on the variety, species spreading, and richness of Pill millipede’s species in different areas of Satara. The newest examination is situated completed to explore the diversity of Pill-millipedes in the aforementioned field because there was a scarcity of systematic data on the Pill-millipedes fauna in the area.

3 Materials and Method

3.1 Study Area

Satara is the part of Deccan trap of the Indian peninsula as shown in Figure 10. The Satara district is divided into the hilly range, tableland, plateau, and plain area. Satara is located at 17.68^{o}N and 73.98^{o}E in Satara district. It lies on the slope of Ajinkyatara Fort, Western side of the Deccan plateau. The Kaas plateau reserved forest is also known as the Kaas pathar. It is a biodiversity hot spot. The study area comprises a forest area.

A survey of three sampling sites of the Western Ghats, foothills of Ajinkyatara fort region (Site A as shown in Figure 7) (17.6723^0 N, 73.9905° E), Bhairoba hill region (Site B as shown in Figure 8) (17.6258^0 N, 74.0872^0 E), and Yavteshwar forest area (Site C as shown in Figure 9) (17.6835^0 N, 73.9507^0 E) during pre and post-monsoon seasons revealed. The occurrence of a variety of Arthrosphaera spp. In the Western Ghats and foothill's locations. An extensive study was conducted from January 2023 to December 2023 and observed the existence of different species of Pill millipedes.

The major plants in the residential area include Tectona grandis (Teak), Mangifera indica (Mango), Artocarpus heterophyllus (jackfruit), Tamarindus indica (Tamarind), Syzygium cumini (Jambhul) Dandrocalamus strictus (Bamboo) and Acacia catechu (Khair). Founded on the availability and accessibility of Pill-millipedes, specimen points were decided diagonally in the study area.

3.2 Collection Method

Researchers collected pill millipedes from the forests, plantations, and foothills regions of the Western Ghats in Satara Tehsil. According to reports by Ashwini (2003) and Kadamannaya (2008, they found 4 adult species of Arthrosphaera (*A. carinata, A. disticta, A. fumosa,* and *A. magna*) in various ecological conditions of the Western Ghats of Satara. The collections took place systematically in the early morning hours, specifically between 6 am to 9 am. A faunistic survey was conducted quarterly over one year, from January 2023 to December 2023. Adult pill millipedes were collected for species examination by hand sorting through forest litter, rotten wood, plant debris, and uppermost soil.

After meticulously washing the adult species with tap water, we placed them in a petri dish and sorted out all materials, preserving them in 70-75% alcohol. We identified the Pill millipedes based on their morphological and taxonomical characteristics, consulting available literature, books, and identification keys by Pocock (1899), Attems (1936), Kadamannaya, and Sridhar (2009), and Kadamannaya et al. (2012).

Overall, the process involved carefully washing the adult species, preserving them in alcohol, and identifying the Pill millipedes based on specific characteristics and literature references. Figure 1 to Figure 4 gives a brief idea about the species collected from the study area during field investigation.

The researchers collected adult species of Arthrosphaera (*A. carinata, A. disticta, A. fumosa,* and *A. magna*) from the forests, plantations, and semi-evergreen forests in different ecological conditions of the Western Ghats of Satara. They conducted surveys in ecological locations in Satara's Western Ghats. They used keys (Pocock 1899; Attems 1936) to reassess and identify the millipedes. The researchers observed adult male and female pill millipedes, focusing on specific body parts (antennae, gnathochilarium, anterior telopod, posterior telopod, and 9th left leg pair, gonophores in males, and vulva and washboard in females) for detailed examination. They carefully assessed the characteristics of each part to determine the final identity.

4 Result

The current study findings indicate that four Pill-millipede species as shown in Figure 1 to Figure 4 from one family have been found in various locations throughout Satara Taluka (Table 1, and Table 2). Rainfall and soil temperature as shown in Figure 5 and Figure 6 were seasonal with rain occurring during June-December, maximum in July, minimum in December (Table 3, and Figure 4).

Four species of Pill millipedes were identified from the study selected spots (Site A, Site B, and Site C) (Figure 1-4). The highest Pill millipede's richness was observed in the Site A and C. The Pill millipede species that were observed belonged 4 species (Table 1).

Climatic factors that overcame nearby the study area are provided in Figure 5 and Figure 6. Through the study period, maximum (37^{0}C) and minimum (21^{0}C) temperatures were recorded in April 2023and December 2023 respectively. The highest rainfall (276 mm) was observed in July 2023.

In the forest ecosystem of montane areas, Pill millipedes play a vital role as good decomposers. In the present study, four species of Pill millipedes were observed. A maximum of five species in the Alagar Hills reserve forest at the southern end of the Eastern Ghats was recorded by Alagasam and Ramanathan (2013). Pill millipedes of the Western Ghats in India were observed by Ambrish C.N. and Sridhar K.R. (2013), who reported general information on the distribution, ecology, conservation, systematics, conservation, and highlighted the gaps in our knowledge on the rare and endemic Pill-millipedes belonging to the genus Arthrosphaera of the Western Ghats of India. Among the soil edaphic features studied, soil temperature and pH were significantly different between monsoon and post-monsoon.

Four species of Pill millipedes (Table 1) were identified from the selected spots altogether. The collected Pill-millipedes sample was identified based on the morphological characteristics such as colour, the structure of the head, antennae, mandibles, thoracic shield, tergites, gnathochilarium, anal shield, and legs, and female and male sexual characters. In the present study, four species of Pill-millipedes such as *Arthrosphaera disticta Pocock*, *Arthrosphaera fumosa Pocock, Arthrosphaera magna Attems, Arthrosphaera Carinata* were identified. These species belong to the genus *Arthrosphera Pocock*, family Arthrosphaeridae Jeekel, and Order Sphaerotheriida Brandt. The current paper focuses on documenting the current knowledge on the distribution, ecology, bioconversion, systematics, and conservation of Arthrosphaera in the Satara Tehsil, Western Ghat, and Maharashtra.

The conservation of Pill-millipedes' species, especially in different unique habitats, is extremely necessary to preserve these species and the ecosystem as a whole. These species need study in various gaps in our knowledge of Pill-millipedes. Studies on the distribution in the Western Ghats, India, have attracted less attention, and there are few studies available on the use of Pill-millipedes to generate compost based on their food and feeding strategies. The study area is provided with climatic factors in Figures 1, 2 and 3. In January 2023, the determined temperature of 37 ^{0}C and the minimum temperature of 21^{0}C were recorded in December 2023. The highest rainfall of 276.3 mm was observed in July 2023. The population thickness and biomass of millipedes were meaningly influenced by atmospheric parameters such as temperature and rainfall with data, moisture. The patterns of richness, distribution, and diversity of most organisms are powerfully affected by the significant difference of abiotic and biotic conservation variations along elevation gradients.

Based on recent surveys, an attempt is made in the present study to update the occurrence, distribution, and morphological description with a diagnostic key for the identification of four species of pill millipedes occurring in the Western Ghats of Satara, with commentary on their distribution pattern in different ecological conditions and the impact of edaphic factors.

In field (distribution and ecology) and laboratory (behaviour and morphology) studies, future-focused attention further strengthens this area of research in understanding the relationship of Arthrosphaera with abiotic and biotic factors in forests, plantations for their conservation and to attach their ecosystem services. This area of research is further enhanced by the forest habitats, where in the present investigation; more moisture content is found in the forest area compared to other areas, and in the present investigation, more common and abundant species of pill millipedes are documented in the forest habitats.

Table 1: Diversity and systematic position of the Pill-millipedes identified

Sr. No.	Family	Order	Genus	Species
1	Arthrosphaeridae	Sphaerotheriida	Arthrosphaera	*A.disticta* Pocock

2	Jeekel, 1974	Brandt, 1833	Pocock, 1895	*A.fumosa* Pocock
3				*A.magna* Attems
4				*A.carinata,*

Figure 1 Arthrosphaera fumosa Pocock

Figure 2 Arthrosphaera carinata

Figure 3 Arthrosphaera disticta

Figure 4 Arthrosphaera magna

Table 2: Comparison of abundance of millipedes at Site A, Site B and Site C

Sr. No.	Species Name	Site A	Site B	Site C	Forest/ Plantation
1	*A.disticta*	+ +	_	+	Forest
2	*A.fumosa*	_	+ +	_	Mixed plantation
3	*A.magna*	+	_	+	Forest
4	*A.carinata*	_	+	+ +	Mixed plantation

Table 3: Rainfall in the study area from January 2023 - December 2023

Month	Rainfall (mm)

January-2023	1
February-2023	1
March-2023	6
April-2023	15
May-2023	34
June-2023	224
July-2023	276.3
August-2023	214.7
September-2023	150
October-2023	87
November-2023	28
December-2023	6

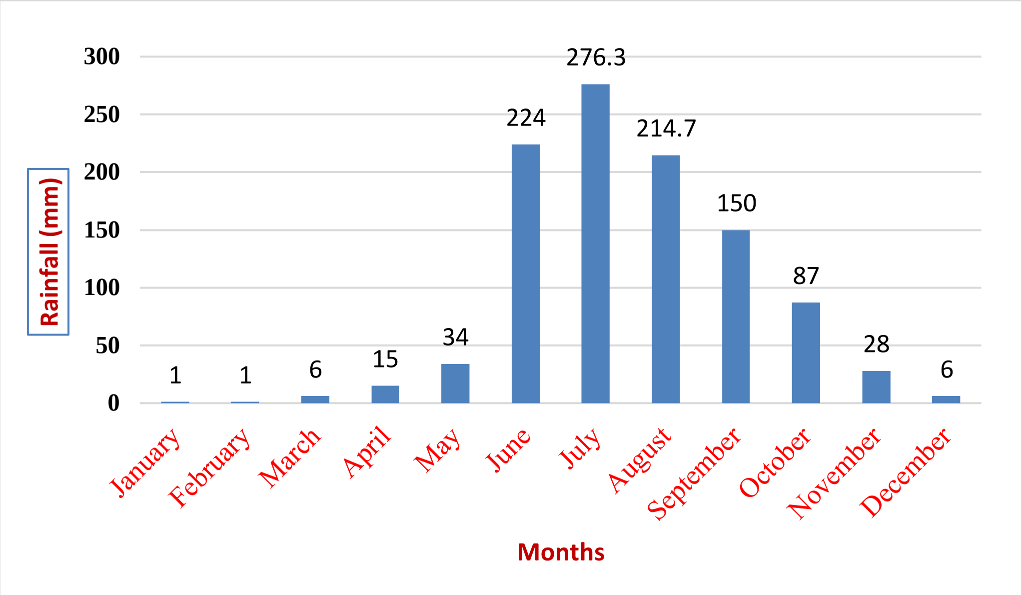

Figure 5 Rainfall (mm) in the study area reported from January 2023 to December 2023

Table: 4 Temperature in the study area from January 2023 to December 2023

Month (2023)	Temperature (^{0}C)
January	21.8
February	23.7
March	36.2
April	37.34
May	27
June	23.9
July	22.3
August	22.2
September	22.7
October	23.7
November	22.8
December	21.6

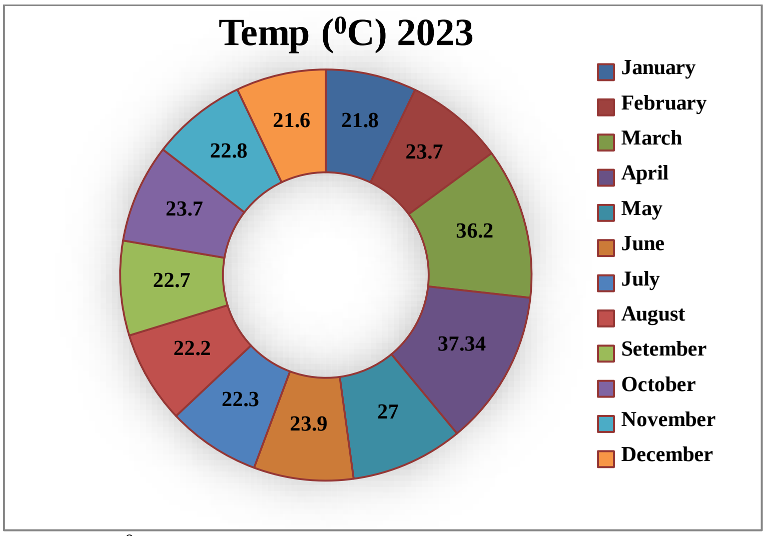

Figure 6 Temperature (^{0}C) in the study area reported from January 2023 to December 2023

5 Conclusion

One of the bio-diverse places in the world is Satara because it is part of the Western Ghats. The Western Ghats, one of the Biodiversity Heritage Sites certified by UNESCO, includes Satara. Satara holds rich diversity, but this group of invertebrate animals is mostly neglected due to complex identification keys and limited literature availability. Satara is considered a biodiversity hotspot, with a vast forested area and thriving agriculture possibly contributing to an increase in Pill millipede species in Satara Tehsil. It is thus necessary to conserve these species and maintain the health of the forest and agriculture ecosystem. The results of the present investigation suggest that pill millipedes are influenced by variations in humidity conditions in their environment. From July to November, a large number of individuals found on the soil surface were leading an active life. The population decreased in January and February. From March onward up to June, virtually no pill millipedes were seen on the surfaces; they were found buried 6 to 9 cm below the surface.

The detailed morphological features have strengthened the characteristics of Arthrosphaera spp. of the Western Ghats of India in the present study. Comparing the specific organs of pill millipedes across the species or genera will greatly refine further classification. The morphology and behaviour of pill millipedes have a direct relationship. For example, pill millipedes lock carinae on pygidium and thoracic shield in conglobation; have ribs on telopods for stridulation, and use telopods, gonopore, and vulva in copulation. The pattern and precise changes during the moulting process in pill millipedes may offer additional clues to elucidate genus or species specific differences. In comparing the genera and species in different adult stages as well as moulting, importance will also be assumed by changes in coloration. Furthermore, for future investigations, the morphological characteristics of pill millipedes of Arthrosphaera will need to be linked with their adaptation and behaviour by effective molecular tools. The evaluation of pill millipede's diversity and abundance was carried out in three different land use systems of Satara taluka. A total of four pill millipedes species belonging to the family were recorded in this current investigation, with the greatest diversity of pill-millipedes being recorded in the forest area compared to other lands. Therefore, it is important to assess their diversity to make informed decisions about environmental management and conservation of sensitive and sentinel pill-millipede species.

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7 Conflict of Interest

There is no conflict of interest including any financial, personal, or other relationships with other people or organizations that can influence their work.

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9 Ethical approval statement

Not applicable.

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Figure 7 Site A Location Map of Study Area Ajinkyatara fort region (17.6723^0 N, 73.9905° E)

Figure 8 Site B Location Map of Study Area Bhairoba hill region (17.6031^0 N, 73.8478^0 E)

Figure 9 Site C Location Map of Study Area Yavteshwar forest (17.6835^0 N, 73.9507^0 E)

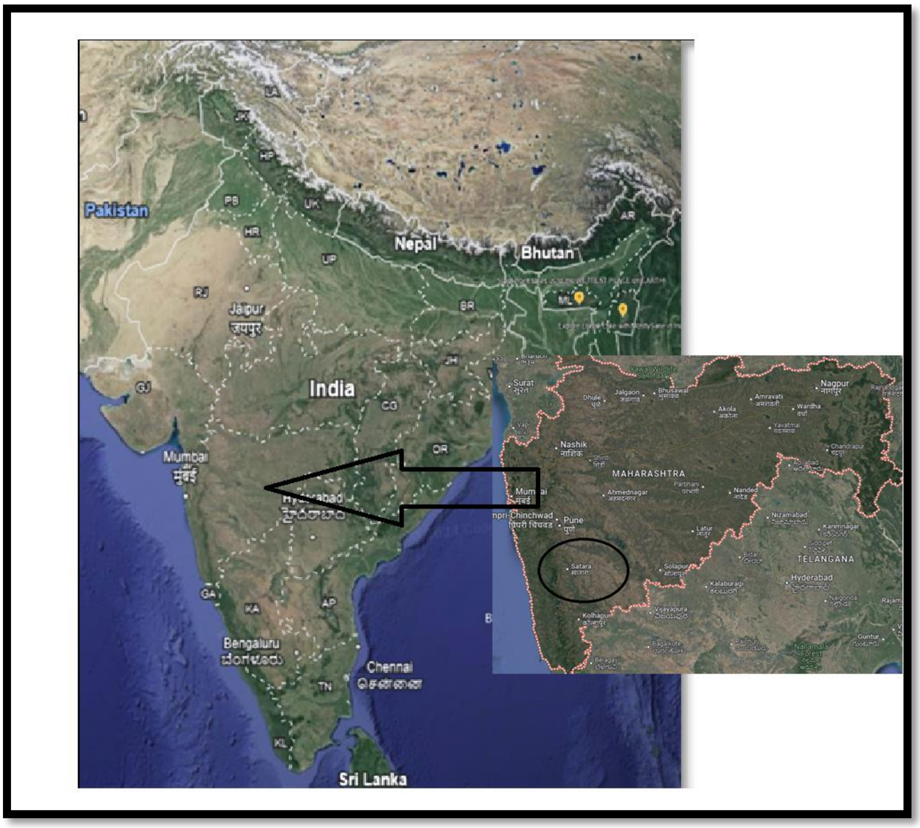

Figure 10 Satellite image of Study are Satara (Maharashtra), India