A Comparative Study on Earthworm Biodiversity & Species Habitat-Relationship of Hilly and Plain Areas of Sirohi District of Rajasthan, India

Suresh Kumar1,*, G. Tripathi2, G. V. Mishra1

1Department of Zoology, Govt. College, Sirohi, India
2Department of Zoology, J. N. V. University, Jodhpur, India
*Corresponding author: sureshgadiveer@gmail.com

Abstract
Extensive surveys of earthworm diversity were done in different habitats of plain and hilly areas of Sirohi district of Rajasthan, India. Earthworms differed in their ecomorphological characteristics and relative abundances in different habitats. A total twelve species of earthworms Pontoscolex corethrurus, Amynthas morrisi, Lampito mauritii, Metaphire posthuma, Metaphire konkanensis, Metaphire houlleti, Perionyx sansibaricus, Polytheretima elongata, Ocnerodrilus occidentalis, Dichogaster bolau, Octochaetona beatrix and Gordiodrilus sp. were recorded from hilly and plain areas. Among these, ten species were found from plain area and nine from hilly area. Five earthworm species (M. konkanensis, M. houlleti, P. elongata, O. beatrix, Gordiodrilus sp.) were recorded for the first-time from Rajasthan. The plain area species P. elongata, O. beatrix and Gordiodrilus sp. were replaced by M. konkanensis and M. houlleti in hilly region. This showed the habitat preferences of earthworm species. Few species were present in a particular habitat of plain area, but they were absent in the same type of habitat in hilly area. The relative density, frequency and species diversity index of earthworm species differed in different habitats and areas. Earthworm diversity exhibited differing species-habitat relationship in hilly and plain areas. These findings may be utilized for eco-restoration of degraded land in similar habitats.

Keywords: earthworm, biodiversity, eco-morphology, density, frequency, diversity index

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1. Introduction

Earthworms represent an important soil faunal group that is widely distributed throughout the world particularly in the temperate and tropical regions and their populations contribute approximately 80% of macrofaunal biomass [1,2] and 8% of total soil biomass in many pedoecosystems [3]. Earthworm diversity is important to study because different ecological groups of earthworms play important role in soil processes and ecosystem services. About 4,400 species of earthworms have been identified worldwide [4]. Munnoli et al. [5] reviewed the earthworm biodiversity indicating a number of species in British Isles (44), France (180), Japan (70), Canada (20), New Zealand (192), Pakistan (15), Libya (3), Australia (300) and India (509). Reynolds and Wetzel [6] reported status and distribution of terrestrial Oligochaeta in Mexico, Puerto Rico, Hawaii, and Bermuda. Martinez et al. [7] found 18 species of earthworms belonging to 13 genera in forest and pastureland of Columbia Andes. Nunes et al. [8] reported 14 earthworm species in four land use systems of Brazil. A total nineteen earthworm species from Tabasco, Mexico have been documented [9]. Ghafoor et al. [10] reported biodiversity of earthworm species from Pakistan. Smith et al. [11] found Aporrectodea as the most common earthworm species in intensively managed in Australia. A total 73 species belonging to 13 genera and 6 families have described from Taiwan [12]. Somniyam and Suwanwaree [13] surveyed the diversity and distribution of terrestrial earthworms of Thailand and reported 19 species belonging to five families. Fifteen earthworm species were recorded by Stojanovic et al. [14] from western and southwestern part of Bulgaria. Teng et al. [15] recorded two species from Peninsular Malaysia. Earthworm richness in land-use systems of Brazil has been investigated [16]. Buckley et al. [17] described 179 earthworms from New Zealand belonging to two families. Boyer et al. [18] described 23 exotic and 200 endemic earthworm species from New Zealand. Eight species of earthworms have been identified from different areas of Bangladesh [19].

A total 509 species belonging to 67 genera and 10 families have been recorded from Indian subcontinent, indicating a high degree of diversity in this region as
compared to other areas [20]. The Indian earthworm fauna is predominantly composed of native species, which constitute about 89% of total earthworm diversity in the country [21]. Earthworm diversity of India exhibited different ecological preferences [22]. Nine species of earthworm have been reported from Jodhpur [23,24]. Population density and distribution of earthworms of Pondicherry region were studied by Sathianarayanan and Khan [25]. Chaudhury et al. [26] recorded a total of 20 species belonging to 10 genera and 5 families from Tripura. Eight earthworm species belonging to five families have been reported from Garhwal [27]. Verma and Shweta [28] recorded 12 species of earthworms from Doon valley. Eight species of earthworms belonging to 5 genera and 3 families have been identified from Kashmir Valley [29]. Khan and Rampal [30] described nine epigeic earthworm species from Jammu where Megascolecidae family was dominant in all the habitats. Western Ghats and coastal plains harbor 218 species of earthworm [31]. Malabar mountain area has its own unique earthworm genera like Celeriella, Lampito, Moniligaster, Notoscolex and Trolia. Haokip and Singh [32] recorded the presence of seven species of earthworms belonging to 5 genera and 4 families from Imphal. Mohan et al. [33] described six genera of earthworms belonging to three families from Amritsar. Siddaraju et al. [34] reported 11 species of earthworm from Mangalore. Six earthworm species belonging to four families were recorded from north Karnataka [35]. Nine species of earthworms belonging to six genera and three families were recorded from transgasgetic plains of Eastern Haryana [36], Yadav [37] described 11 species of earthworms from Tamil Nadu. Parthasarathi et al. [38] documented earthworm diversity of Cauvery delta with nine species belonging to seven genera and four families. Seventeen species of earthworms belonging to six different families were recorded from Assam [39]. Goswami and Mondal [40] reported six species of earthworms from South 24 parganas of West Bengal. Singh et al. [41] reported five species of earthworms belonging to two families from Punjab. Narayanan et al. [42] reported two earthworm species from Kerala. Total fifty species of earthworm belonging to six families were documented from Uttar Pradesh [43]. Ten species of earthworm belonging to two families were recorded from Odisha [44]. Eight species of earthworm were recorded from Kolkata [45]. Ten species of earthworms belonging to five families were reported from south India [46] Singh et al. [47] reported ten earthworm species from cultivated and non-cultivated agroecosystems of Kathua.

Most species of earthworms prefer soil with a temperature of 10-35°C, moisture of 12-34%, pH of about 7 and C:N ratio 2-18 [48,49,50]. Generally, they are absent or rare in soil with a very coarse texture and high clay content, or soil with pH<4 [51]. Martin and Lavelle [52] investigated the distribution of worms within the soil profile and related abiotic and biotic factors. Ganihar [53] studied earthworm distribution with reference to physico-chemical parameters of soil. Karmegam and Daniel [54] correlated the population dynamics and biomass of Pontoscolex corethrurus with climatic and physico-chemical parameters. Earthworm populations in cultivated land were generally lower than those found in undisturbed habitats [55]. The earthworm community structure in agroecosystem is determined by soil type [56]. Management practices applied to soils may have some positive or negative effects on earthworm abundance and diversity [57]. Soil temperature and moisture affect the diversity of earthworms [58]. Chaudhury et al. [26] observed that the suitable temperature, moisture, aerobicty of soil create favorable microclimatic conditions for earthworms. Turbe et al. [59] reported that soil texture and structure strongly influence the activity of soil biota. Medium-textured loam and clay soils favor microbial and earthworm activity, whereas fine textured sandy soils, with lower water retention potentials, are less favorable. Soil salinity, which may increase near the soil surface, can also cause severe stress to soil organisms, leading to their rapid desiccation. Similarly, changes in soil pH can affect the metabolism of species by affecting the activity of enzymes and nutrient availability and are thereby often lethal to soil organisms. Mariappan et al. [60] observed that the abundance of earthworm in different habitats are greatly influenced by soil physiochemical characteristics such as pH, electrical conductivity, organic carbon, organic matter, total nitrogen, phosphorus, potassium and C:N ratio. Sharma and Bhardwaj [36] suggested that microclimatic factors and anthropogenic activities influence the earthworm diversity. Chauhan [61] showed that the disturbances in natural system alter the habitat of soil biota and in some cases make the habitat unfavorable for earthworms.

Soil cultivation may cause mechanical damage to earthworms or expose them to predation. Elazirg Elammary et al. [62] performed a comparative study on the earthworm resources of Benghazi, Libya and Kollam district, India (Tropical humid biome), both having different environmental and physiographical conditions. A significant positive correlation existed between the density of earthworms and percent of sand, and a significant inverse correlation existed between the density of earthworms and organic matter and percent clay in Benghazi, whereas a significant inverse correlation existed between density of earthworms and soil temperature in Kollam district. Baireddy et al. [63] found that the earthworm population gradually declined with the increase in the depth of the soil. Most of the earthworms were present in top layer (0-15 cm) of the soil [64, 65], which suggested that lack of oxygen and dryness in depth of soil limits the earthworm distribution. In retrospect of the above view no study has been done to compare the earthworm diversity and abundance in relation to physicochemical characteristic of soil system in hilly and plain areas. Soil organisms like earthworms play significant role in improvement of agricultural soil and contribute to well-being and welfare of farmers, consumers and people [66]. The hypothesis was to know whether hilly and plain areas harbor the same species diversity and how this diversity is related to habitats. Therefore, it was decided to investigate the earthworm biodiversity and species habitat relationship in hilly and plain areas of Sirohi district of Rajasthan.
2. Material and Methods

2.1. Sampling

Various sites of all the five tehsils of Sirohi (viz., Sirohi, Sheoganj, Reodar, Pindwara and Abu road) were surveyed for earthworm species diversity (Figure 1). In Abu road tehsil Mount Abu is hilly area and other parts are plain. The names of surveyed sites are given in Table 1. Biodiversity surveys were carried out in different months during the period from 2015 to 2016 in various habitats. Earthworm and soil samplings were done every month from each site at an interval of ten days. Sampling quadrate was established at each site, containing five units of one square meter. Earthworms were collected by digging soil monolith and hand sorting method as described by Julka [67]. They were sorted out manually and counted. Collected worms were kept in sample carrying bags with a little moist soil and brought to laboratory. They were washed and preserved in 5-10% formalin. Earthworms were identified with the help of morphological features and taxonomic key. The help of monographs and other available literatures [67,68,69] were also taken for identification of earthworms. All the collected species were finally confirmed by expert.

Table 1. Random survey of earthworm biodiversity and physiochemical characteristics of different sites of Sirohi district of Rajasthan

| S. No. | Site (habitat)                        | Earthworm species                  | Soil Temp. (°C) | pH  | Soil Moist. (%) | EC (dSm⁻¹) | OC (%) | OM (%) | TN (%) | C/N ratio |
|--------|--------------------------------------|------------------------------------|----------------|-----|----------------|------------|--------|--------|--------|-----------|
| 1      | Sirohi (Agricultural land)           | Lampito mauritii                   | 24.2           | 8.7 | 15.71          | 0.91       | 0.33   | 0.57   | 0.08   | 3.93      |
| 2      | Sirohi (Botanical garden College campus) | Metaphire posthuma Octochaetona beatrix | 23.8           | 8.5 | 24.22          | 0.86       | 0.45   | 0.78   | 0.11   | 4.02      |
| 3      | Sirohi (Kitchen garden)              | Dichogaster bolaui Lampito mauritii | 23.4           | 8.1 | 18.06          | 0.79       | 0.48   | 0.83   | 0.12   | 4.03      |
| 4      | Sirohi (Domestic sewage)             | Dichogaster bolaui Gordiodrilus sp. | 23.0           | 8.1 | 26.26          | 0.81       | 0.66   | 1.14   | 0.07   | 9.43      |
| 5      | Sirohi (Orchard)                     | Lampito mauritii Gordiodrilus sp.   | 25.0           | 8.4 | 18.48          | 0.68       | 0.45   | 0.78   | 0.08   | 5.84      |
| 6      | Palari R, Sirohi (Waste land)        | Lampito mauritii                   | 26.2           | 7.8 | 5.82           | 0.65       | 0.24   | 0.41   | 0.06   | 3.81      |
| 7      | Sirohi (Saradham Temple plantation)  | Pontoscolex corethrurus            | 28.2           | 8.7 | 25.00          | 0.73       | 0.42   | 0.73   | 0.08   | 5.00      |
| 8      | Sirohi (Gandhi public park)          | Lampito mauritii Octochaetona beatrix | 25.4           | 8.3 | 18.48          | 0.81       | 0.45   | 0.78   | 0.08   | 5.36      |
| 9      | Doduva, Sirohi (Bhuvneshvar Mahadev Temple garden) | Lampito mauritii                   | 26.4           | 8.9 | 21.36          | 0.62       | 0.48   | 0.83   | 0.10   | 4.90      |
| 10     | Rampura, Sirohi (Waste land)         | Lampito mauritii                   | 27.2           | 8.0 | 5.71           | 0.72       | 0.36   | 0.62   | 0.08   | 4.29      |
| 11     | Jawal, Sirohi (Agricultural land)    | Lampito mauritii                   | 22.4           | 8.1 | 15.34          | 0.67       | 0.27   | 0.47   | 0.09   | 2.97      |
| S. No. | Site (habitat)           | Earthworm species                                      | Soil Temp. (°C) | pH | Soil Moist. (%) | EC (dSm⁻¹) | OC (%) | OM (%) | TN (%) | C/N ratio |
|-------|--------------------------|--------------------------------------------------------|-----------------|----|----------------|------------|--------|--------|--------|-----------|
| 12.   | Posaliya, Sheoganj       | Metaphire posthuma, Octochaetona beatrix              | 23.8            | 8.7| 24.53          | 0.52       | 0.36   | 0.62   | 0.13   | 2.86      |
| 13.   | Sheoganj (Garden)        | Lamptio mauritii, Dichogaster bolaui Octochaetona beatrix | 18.2            | 8.9| 25.63          | 0.33       | 0.78   | 1.35   | 0.15   | 5.31      |
| 14.   | Sheoganj Roadside (near water tank) | Dichogaster bolaui                                 | 20.2            | 8.4| 32.28          | 0.87       | 0.48   | 0.83   | 0.06   | 8.57      |
| 15.   | Posaliya, Sheoganj       | Pontoscolex corethrurus                               | 21.4            | 8.6| 15.74          | 0.47       | 0.96   | 1.66   | 0.11   | 8.57      |
| 16.   | Sheoganj (Orchard)       | Dichogaster bolaui Octochaetona beatrix               | 19.0            | 7.8| 19.90          | 0.33       | 0.60   | 1.04   | 0.09   | 6.59      |
| 17.   | Sheoganj (Agricultural land) | Pontoscolex corethrurus                           | 21.2            | 8.2| 26.26          | 0.35       | 0.33   | 0.57   | 0.08   | 3.93      |
| 18.   | Pindwara (Roadside)      | Lamptio mauritii                                      | 22.5            | 8.2| 11.36          | 0.26       | 0.18   | 0.31   | 0.07   | 2.57      |
| 19.   | Pindwara (Pastureland)   | Lamptio mauritii                                      | 28.2            | 8.3| 7.07           | 0.28       | 0.24   | 0.41   | 0.08   | 2.86      |
| 20.   | Jharoli, Pindwara (Sewage)| Dichogaster bolaui                                    | 26.8            | 7.4| 25.63          | 0.63       | 0.36   | 0.62   | 0.06   | 6.43      |
| 21.   | Pindwara (Agricultural land) | Lamptio mauritii                                    | 23.6            | 8.7| 15.74          | 0.91       | 0.21   | 0.36   | 0.06   | 3.75      |
| 22.   | Reodar (Agricultural land)| Lamptio mauritii, Dichogaster bolaui                | 23.8            | 8.6| 28.53          | 0.30       | 0.27   | 0.47   | 0.08   | 3.21      |
| 23.   | Bherutarak, Reodar (Agricultural land) | Pontoscolex corethrurus                | 26.2            | 8.1| 31.58          | 0.47       | 0.33   | 0.57   | 0.11   | 2.95      |
| 24.   | Pitapura, Reodar (Agricultural land) | Lamptio mauritii, Octochaetona beatrix            | 22.8            | 8.9| 16.55          | 0.77       | 0.24   | 0.41   | 0.07   | 3.43      |
| 25.   | Bherutarak, Reodar (nursery) | Lamptio mauritii                                  | 24.0            | 7.9| 25.00          | 0.25       | 0.54   | 0.93   | 0.10   | 5.51      |
| 26.   | Anadara, Reodar (Roadside)| Lamptio mauritii                                    | 26.0            | 7.4| 18.76          | 0.27       | 0.24   | 0.41   | 0.09   | 2.64      |
| 27.   | Bherutarak, Reodar (Forest land) | Lamptio mauritii, Pontoscolex corethrurus | 22.4            | 7.7| 14.29          | 0.57       | 0.60   | 1.04   | 0.12   | 5.04      |
| 28.   | Aburoad (Agricultural land) | Lamptio mauritii, Polychaeretina elongata        | 26.2            | 8.3| 31.58          | 0.26       | 0.33   | 0.57   | 0.08   | 3.93      |
| 29.   | Aburoad (Sewage)         | Perionyx sansibaricus                                | 25.8            | 7.9| 35.87          | 0.67       | 0.69   | 1.19   | 0.07   | 9.86      |
| 30.   | Aburoa (Grassland)       | Ocnerodrilus occidentalis                            | 24.6            | 7.8| 14.94          | 0.38       | 1.20   | 2.07   | 0.10   | 12.2      |
| 31.   | Aburoad (Vanjana dam coastal area) | Amynthas morrisi, Lamptio mauritii | 23.8            | 7.6| 13.64          | 0.53       | 0.33   | 0.57   | 0.08   | 3.93      |
| 32.   | Mount Abu (Sewage roadside) | Lamptio mauritii, Perionyx sansibaricus, Ocnerodrilus occidentalis | 20.2            | 7.4| 26.58          | 0.26       | 0.78   | 1.35   | 0.08   | 10.1      |
| 33.   | Mount Abu (Sewage)       | Amynthas morrisi, Metaphire houlleti                | 20.4            | 7.8| 18.48          | 0.32       | 0.78   | 1.35   | 0.09   | 8.57      |
| 34.   | Mount Abu (Grassland)    | Lamptio mauritii, Pontoscolex corethrurus           | 18.2            | 7.5| 26.90          | 0.39       | 1.50   | 2.59   | 0.12   | 12.6      |
| 35.   | Mount Abu (Forest land)  | Megascolex komkaneini, Lamptio mauritii, Pontoscolex corethrurus, Amynthas morrisi | 18.4            | 7.0| 14.42          | 0.38       | 0.66   | 1.14   | 0.13   | 5.24      |
| 36.   | Mount Abu (Garden near Naki lake) | Metaphire posthuma, Amynthas morrisi | 19.0            | 8.3| 28.21          | 0.61       | 0.90   | 1.56   | 0.14   | 6.43      |
| 37.   | Mount Abu (Kodhra Dam coastal area, waste land) | Amynthas morrisi, Pontoscolex corethrurus | 19.2            | 7.4| 18.20          | 0.43       | 0.27   | 0.47   | 0.11   | 2.41      |
| 38.   | Mount Abu (Agricultural land) | Lamptio mauritii, Amynthas morrisi                  | 18.8            | 8.0| 20.19          | 0.53       | 0.24   | 0.41   | 0.08   | 2.86      |
| 39.   | Mount Abu (Orchard)      | Lamptio mauritii, Dichogaster bolaui                | 21.4            | 7.8| 21.95          | 0.43       | 0.48   | 0.83   | 0.12   | 4.03      |
| 40.   | Mount Abu (Sewage)       | Dichogaster bolaui, Pontoscolex corethrurus         | 22.2            | 7.9| 32.98          | 0.67       | 0.72   | 1.24   | 0.09   | 7.91      |

Temp., Temperature; Moist., Moisture; EC, Electric conductivity; OC, Organic carbon; OM, Organic matter; TN, Total nitrogen; C/N ratio; carbon/nitrogen ratio.
2.2. Collection and Analysis of Soil Samples

Soil samples were collected from surface up to 25 cm depth with the occurrence of earthworms. Collections of earthworms and soils were done throughout the year to establish species-habitat relationship. Different soil parameters were estimated and values of two consecutive years are presented in Table. The soil pH (1:5w/v) and electric conductivity were recorded by a digital pH meter and electric conductivity meter respectively. The moisture content of soil was estimated gravimetrically on wet basis by oven drying at 105°C, while other parameters were analyzed from air-dried soil sieved through 2 mm sieve. The organic carbon of the soil sample was measured by Walkley-Black method [70]. The total nitrogen was calculated by Macro-Kjeldahl method as described by Anderson and Ingram [71]. Available phosphorus was extracted with sodium bicarbonate [72] and estimated has described by Blackmore et al. [73]. The exchangeable potassium cation was determined after extracting the soil using ammonium acetate-extractable method [74]. The C/N ratio was calculated from the measured values of C and N.

2.3. Habitat Relationship and Qualitative Composition

Earthworms were collected regularly from various ecological niches such as kitchen drainage, sewage, gardens, margins of freshwater bodies, pasture, grassland, forest, cultivated fields etc. The number of each earthworm species recorded per square meter area was categorized as abundant (>20), moderate (11-20), poor (1-10) and absent (0). The ecological categories of earthworm species were also finalized. The pH, temperature, moisture and nutrients of soil were recorded. From these areas certain study sites viz., cultivated, non-cultivated, garden, sewage, forest, orchard and grass land were selected to observe average density. Seasonal changes in the population of earthworm species were recorded. Collected worms were sorted into immature and mature forms for counting. Relative density, biomass, frequency, species diversity index [75], index of dominance [76], index of species richness [77], index of evenness [78] and effective number of species or Hill number [79] were calculated for some selected habitats.

3. Results

3.1. Species Diversity

A total 12 species of earthworms were recorded from hilly and plain areas of Sirohi district of Rajasthan. These species were Pontoscolex corethrurus, Aminthas morrisi, Lampito mauritii, Metaphire posthuma, Megascolex konkanensis, Metaphire houlleti, Perionyx sansibaricus, Polytheretima elongata, Ocnerodrilus occidentalis, Dichogaster bolai, Gordiodrilus sp. and Octochaetona beatrix (Figure 2). Maximum number of species was recorded from Abu road tehsil including hilly areas of Mount Abu (Table 2, Figure 3A). A moderate number of species was observed from Sirohi, Sheoganj and Reodar tehsils. However, the occurrence of earthworm species in Pindwara tehsil was poor comprising only two species. Ten earthworm species were found in Abu road tehsil. However, nine species were recorded from hilly area (Mount Abu). Among these four species (Aminthas morrisi, Lampito mauritii, Perionyx sansibaricus, Ocnerodrilus occidentalis) were common in both plain and hilly areas. The earthworm Polytheretima elongata was observed only from Abu road, whereas Megascolex konkanensis and Metaphire houlleti were present in Mount Abu but they were not recorded from other parts of Sirohi district. Sirohi tehsil showed the presence of six species (Pontoscolex corethrurus, Metaphire posthuma, Lampito mauritii, Dichogaster bolai, Gordiodrilus sp., Octochaetona beatrix). Five species (Dichogaster bolai, Lampito mauritii, Metaphire posthuma, Octochaetona beatrix, Pontoscolex corethrurus) were recorded from Sheoganj tehsil. Four earthworm species (Lampito mauritii, Dichogaster bolai, Pontoscolex corethrurus, Octochaetona beatrix) were found in Reodar tehsil. While Pindwara tehsil showed the presence of Lampito mauritii and Dichogaster bolai.

3.2. Ecomorphological Characteristics

The earthworm species recorded from various parts of Sirohi district exhibited different eco-morphological characteristics (Table 3). The earthworms, which did not show any pigmentation, were referred to as colourless. The individuals of A. morrisi were reddish brown in colour having 70-145 mm body length, 3.9-5.0 mm diameter and 110-145 body segments. They were epi-aneic. The earthworms L. mauritii and P. elongata were members of anecic category. L. mauritii was light pink in colour with 75-155 mm length, 3.8-5.0 mm diameter and 80-172 segments but P. elongata was whitish in colour with body length of 170-200 mm, 4.2-5.5 mm diameter and 140-185 segments. The earthworm species M. posthuma and M. houlleti were endo-aneic. M. posthuma was dark brown in colour with 65-138 mm length, 4.0-5.2 diameters and 100-132 body segments, whereas M. houlleti was reddish with 65-140 mm body length, 4.0-5.0 mm diameter and 110-155 segments. P. sansibaricus, D. bolai and Gordiodrilus sp. belongs to epigeic category, P. sansibaricus had dark purple colour with body length of 82-116 mm, 2.0-3.5 mm diameter and 95-138 body segments. D. bolai was whitish in colour having 28-48 mm body length, 1.5-3.0 mm diameter and 65-98 body segments. However, Gordiodrilus sp. was light pale colour with 20-48 mm body length, 0.9-1.7 mm diameter and 65-92 body segments. Rests of the four earthworm species (viz., P. corethrurus, M. konkanensis, O. occidentalis and O. beatrix) were endogeic. P. corethrurus was pale brown in colour having 128-160 mm body length, 3.7-4.8 diameter and 126-170 segments. M. konkanensis was light pale in colour with 142-180 in body length, 3.8-4.6 diameter and 132-178 segments. The earthworm species O. occidentalis was whitish in colour having 15-45 mm body length, 0.8-1.6 mm diameter and 66-89 body segments. Whereas O. beatrix was pale yellow colour with 55-98 mm length, 1.8-3.8 mm diameter and 46-120 body segments. However, P. elongata was longest and heavier, but O. occidentalis was shortest and light weighed.
Figure 2. Diversity of earthworm species recorded from hilly and plain areas of Sirohi District of Rajasthan

Table 2. Tehsil-wise occurrence of earthworm species in Sirohi district of Rajasthan

| Family             | Species                          | Sirohi | Sheoganj | Reodar | Pindwara | Aburoad |
|--------------------|----------------------------------|--------|----------|--------|----------|---------|
| 1. Glossoscolecidae | 1. Pontoscolex corethrurus        | +      | +        | +      | -        | +       |
| 2. Megascolecidae  | 1. Amynthas morrisi              | -      | -        | -      | -        | +       |
|                    | 2. Lampito mauriti               | +      | +        | +      | +        | +       |
|                    | 3. Metaphire posthuma            | +      | +        | -      | -        | +       |
|                    | 4. Metaphire houletti            | -      | -        | -      | -        | +       |
|                    | 5. Megascolex konkamensis        | -      | -        | -      | -        | +       |
|                    | 6. Perionyx sansibaricus         | -      | -        | -      | -        | +       |
|                    | 7. Polypheretima elongata        | -      | -        | -      | -        | +       |
| 3. Ocnerodrilidae  | 1. Ocnerodrilus occidentalis     | -      | -        | -      | -        | +       |
| 4. Octochaetidae   | 1. Dichogaster bulaui            | +      | +        | +      | +        | +       |
|                    | 2. Gordiodrilus sp.              | +      | -        | -      | -        | -       |
|                    | 3. Octochaetona beatris          | +      | +        | +      | -        | -       |

| Total              | 12     | 6       | 5       | 4       | 2        | 10      |

+ Present; - Absent.
3.3 Qualitative Composition of Earthworms

A total twelve species of earthworm were recorded from hilly and plain regions of Sirohi district of Rajasthan comprising *P. corethrurus*, *A. morrisi*, *L. mauritii*, *M. posthuma*, *M. konkanensis*, *M. houlleti*, *P. sansibaricus*, *P. elongata*, *O. occidentalis*, *D. bolaui*, *G. sp.* and *O. beatrix*. Out of these twelve earthworms, ten species were found in plain area and nine in hilly region. The earthworm species of plain area *P. elongata*, *Gordiodrilus sp.* and *O. beatrix* were replaced by *M. konkanensis* and *M. houlleti* in hilly region (Table 4, Figure 3B). Population densities of earthworms in various habitats of plain and hilly areas of Sirohi district were studied (Table 5a, Table 5b and Figure 4A-G). The combined average population density of earthworms has been mentioned in Table 6. Table 7 indicates the density of earthworms in three categories viz., abundant (>20/m²), moderate (11-20/m²) and poor (1-10/m²) in plain and hilly regions. However, Table 8 illustrates category-wise combined average density of earthworms in different habitats of Sirohi district. Earthworm species *M. posthuma* was moderately found in cultivated land of plain area but was absent in cultivated ecosystems of hilly area. *L. mauritii* moderately occurred in both plain and hill, while poor population density of *A. morrisi* was recorded in agroecosystem of hilly region and was absent in cultivated land of plain area. Whereas *P. corethrurus*, *P. elongata* and *O. beatrix* showed poor presence in cultivated agroecosystem of plain area. They were not recorded from agricultural lands of hilly zone. However, *M. houlleti*, *M. konkanensis*, *P. sansibaricus*, *O. occidentalis* and *Gordiodrilus sp.* were absent in cultivated land.

In non-cultivated field *D. bolaui*, *L. mauritii*, *P. corethrurus* and *A. morrisi* showed their poor populations. *A. morrisi* was found in non-cultivated field of both plain and hilly areas, while *P. corethrurus* was found in non-cultivated field of hilly area only. *D. bolaui* and *L. mauritii* were found in non-cultivated field of plain region. No individuals of *M. posthuma*, *M. houlleti*, *M. konkanensis*, *P. elongata*, *P. sansibaricus*, *O. occidentalis*, *Gordiodrilus sp.* and *O. beatrix* were recorded from such habitats. The occurrence of five earthworm species viz., *A. morrisi*, *L. mauritii*, *D. bolaui*, *M. posthuma* and *O. beatrix* were in garden. Moderate number of *M. posthuma* was found in garden land of plain and hilly areas. Occurrence of *L. mauritii* and *D. bolaui* showed moderate density in garden land of plain area and both were absent from hilly region garden pedoecosystem.
A. morrisi was poorly recorded from garden land of hilly region and was zero in garden land of plain area. Whereas a poor density O. beatrix was obtained in garden land of plain area and was completely absent from hilly region.

In contrast the earthworm species M. houlleti, M. konkanensis, P. corethrurus, P. elongata, P. sansibaricus, O. occidentalis and Gordiodrilus sp. were absent in garden soil.

### Table 4. Plain and hilly area-wise distribution of earthworm species of Sirohi district of Rajasthan

| Species          | Plain | Hill |
|------------------|-------|------|
| 1. Glossoscolecida | +     | +    |
| 2. Megascolecida  | +     | +    |
| 3. Oenotheriidae  | +     | +    |
| 4. Octochaetidae  | +     | +    |
| Total            | 12    | 10   |

+ Present; - Absent

### Table 5a. Densities (worm×m⁻²) of earthworms in different habitats of plain and hilly area of Sirohi district of Rajasthan. Each datum is the average value of observations during random surveys

| Family           | Species                        | Plain Value | Hill Value |
|------------------|--------------------------------|-------------|------------|
| 1. Glossoscolecida | 1. Pontoscoles corethrurus      |             |            |
| 2. Megascolecida  | 1. Amynthas morrisi             |             |            |
| 3. Oenotheriidae  | 1. Oenotheria occidentalis      |             |            |
| Total            | 12                             | 10          | 9          |

### Table 5b. Densities (worm×m⁻²) of earthworms in different habitats of plain and hilly area of Sirohi district of Rajasthan. Each datum is the average value of observations during random surveys

| Habitat         | Forest land      | Sewage soil     | Grass land     |
|-----------------|------------------|-----------------|----------------|
| A. morrisi      | 0.00             | 9.72±0.28       | 0.00           |
| D. bolani       | 0.00             | 22.13±0.21      | 23.33±0.35     |
| Total           | 9.42±0.21        | 13.74±0.20      | 22.33±0.35     |

| Habitat         | Forest land      | Sewage soil     | Grass land     |
|-----------------|------------------|-----------------|----------------|
| A. morrisi      | 0.00             | 22.13±0.21      | 23.33±0.35     |
| D. bolani       | 0.00             | 23.33±0.35      | 22.33±0.35     |
| Total           | 9.42±0.21        | 13.74±0.20      | 22.33±0.35     |
Figure 4. Density (worm×m⁻²) of earthworms in cultivated (A), non-cultivated (B), garden (C) orchard (D), forest (E) sewage (F) and grass (G) lands of plain and hilly areas of Sirohi district. Each datum is the average value of observations during random surveys.

Table 6. Densities (worm×m⁻²) of earthworms in different habitats of Sirohi district of Rajasthan. Each datum is the average value of observations during random surveys.

| Habitat species       | Cultivated land | Non-cultivated land | Garden land | Orchard land | Forest land | Sewage soil | Grass land |
|-----------------------|-----------------|---------------------|------------|--------------|-------------|-------------|------------|
| *A. morrisi*          | 8.03±0.02       | 7.51±0.23           | 9.28±0.12  | 0.00         | 9.27±0.28   | 13.74±0.20  | 0.00       |
| *D. bolaui*           | 9.77±0.09       | 7.29±0.06           | 14.69±0.07 | 25.36±1.49   | 0.00        | 22.76±0.31  | 0.00       |
| *Gordiodrilus* sp.    | 0.00            | 0.00                | 11.33±0.35 | 0.00         | 20.36±0.12  | 0.00        | 0.00       |
| *L. mauritii*         | 13.04±0.76      | 7.37±0.11           | 10.06±0.01 | 9.65±0.75    | 17.45±1.51  | 5.71±0.30   | 6.33±0.20  |
| *M. konkanensis*      | 0.00            | 0.00                | 0.00       | 0.00         | 16.58±0.27  | 0.00        | 0.00       |
| *M. houleti*          | 0.00            | 0.00                | 0.00       | 0.00         | 12.11±0.23  | 0.00        | 0.00       |
| *M. posthuma*         | 10.39±0.18      | 0.00                | 15.67±0.86 | 0.00         | 0.00        | 0.00        | 0.00       |
| *O. beatrix*          | 5.97±0.20       | 0.00                | 8.64±0.01  | 9.54±0.16    | 0.00        | 0.00        | 0.00       |
| *O. occidentalis*     | 0.00            | 0.00                | 0.00       | 0.00         | 14.25±0.36  | 21.67±0.36  | 0.00       |
| *P. corethrurus*      | 8.98±0.02       | 6.99±0.10           | 0.00       | 7.63±0.94    | 14.12±0.45  | 9.46±0.69   | 0.00       |
| *P. elongata*         | 8.44±0.04       | 0.00                | 0.00       | 0.00         | 17.07±0.29  | 0.00        | 0.00       |
| *P. sansibaricus*     | 0.00            | 0.00                | 0.00       | 0.00         | 0.00        | 0.00        | 0.00       |
| F-value               | 19.75           | 1.05                | 22.98      | 51.48        | 17.86       | 577.27      | 118.86     |
| P-value               | <0.001          | >0.05(*NS)          | <0.001     | <0.001       | <0.001      | <0.001      | <0.001     |
| Total earthworm density (No./m²) | 64.62 | 25.16 | 57.65 | 55.88 | 50.93 | 140.12 | 37.46 |

*NS; Non-significant.
The population of *D. bolaui* was abundantly found in orchard pedoecosystem of both hilly and plain areas. While the density of *L. mauritii* was moderately recorded in orchard land of hilly area and was poor in orchard land of plain area. *Gordiodrilus* sp. was moderate and *O. beatrix* was poor in orchard land of plain area. They were zero in orchard land of hilly area. Whereas the earthworm species *A. morrisi*, *M. posthuma*, *M. houlleti*, *M. konkanensis*, *P. corethrurus*, *P. elongata*, *P. sansibaricus* and *O. occidentalis* were not recorded from this ecosystem. The earthworm species *L. mauritii* was recorded abundantly, while *P. corethrurus* was poorly found in forest land of both regions. Moderate density of *M. konkanensis* was reported in forest land of hilly region and was absent in forest land of plain area. *A. morrisi* was poor in forest land of hilly area and absent in plain area forest land. In contrast no member of *D. bolaui*, *M. posthuma*, *M. houlleti*, *P. elongata*, *P. sansibaricus*, *O. beatrix*, *O. occidentalis* and *Gordiodrilus* sp. were recorded from forest land.

*D. bolaui* was abundantly found in the sewage pedoecosystem of both regions. While *Gordiodrilus* sp. and *O. occidentalis* was abundantly found in sewage soil of hilly and plain area respectively. *Gordiodrilus* sp. was absent in hilly area and *O. occidentalis* was absent in sewage system of plain area. The sewage soils of plain and
hilly areas represent moderate density of *P. sansibaricus*. The earthworm species *P. corethrurus*, *M. houlleti* and *A. morrisi* population were moderately found in sewage soil of hilly area and showed zero population in plain area sewage system. The poor density of *L. mauritii* was found in sewage land of hilly area. It was absent in plain region sewage soil. No individuals of *P. elongata*, *M. konkanensis*, *M. posthuma* and *O. beatrich* were recorded from sewage system of Sirohi district. In contrast to sewage system, grass land showed the abundance of *O. occidentalis* in plain area, while it was not found in grass land system of hilly region. *P. corethrurus* was moderately found in grass land pedoecosystem of hilly area but poorly in found in plain area grass land. While the earthworm species *L. mauritii* was poor in grass land of hilly region and absent in grass land system of plain area. In grass land the population of *A. morrisi*, *D. bolaui*, *M. konkanensis*, *M. posthuma*, *H. houlleti*, *P. elongata*, *P. sansibaricus*, *O. beatrich* and *Gordiodrilus* sp. were absent.

### 3.4. Species-habitat Relationship

Earthworms in relation to physicochemical characteristics of different pedoecosystems of plain and hilly regions were studied (Table 9a, Table 9b). Table 10 illustrates the average values of physicochemical parameters of various habitats of Sirohi district. Six earthworm species i.e., *P. corethrurus*, *L. mauritii*, *M. posthuma*, *P. elongata*, *D. bolaui* and *O. beatrich* were recorded from cultivated field of plain area having 18.8-36.4°C temperature, 7.4-8.1 pH, 15.34-31.58% moisture, 0.26-0.91dSm⁻¹ electrical conductivity, 0.21-0.36% organic carbon, 0.36-0.62% organic matter, 0.06-0.13% total nitrogen, 2.86-3.93 C/N ratio, 0.30-0.41mgkg⁻¹ potassium, 6.62-9.85mgkg⁻¹ phosphorus, 3.25-7.78mgkg⁻¹ NH₄-N and 2.54-5.15mgkg⁻¹ NO₃-N. In comparison to cultivated land of plain area, hilly region had only two species *A. morrisi* and *L. mauritii* having 16.8-35.0°C temperature, 7.2-8.0 pH, 20.19-31.58% moisture, 0.35-0.53 dSm⁻¹ electrical conductivity, 0.24-0.54% organic carbon, 0.41-0.93% organic matter, 0.08-0.11% total nitrogen, 2.86-5.14 C/N ratio, 0.31-0.48mgkg⁻¹ potassium, 6.26-9.00mgkg⁻¹ phosphorus, 5.65-6.00mgkg⁻¹ NH₄-N and 3.00-4.60mgkg⁻¹ NO₃-N.

A total four earthworm species (*A. morrisi*, *L. mauritii*, *P. corethrurus*, *D. bolaui*) were found in non-cultivated land of Sirohi. *A. morrisi*, *L. mauritii* and *D. bolaui* were reported from non-cultivated field of plain area having 20.2-37.8°C temperature, 7.4-8.4 pH, 5.71-32.28% moisture, 0.27-0.87dSm⁻¹ electrical conductivity, 0.18-0.48% organic carbon, 0.31-0.83% organic matter, 0.06-0.09% total nitrogen, 2.57-8.57 C/N ratio, 0.18-0.35mgkg⁻¹ potassium, 4.28-7.35mgkg⁻¹ phosphorus, 3.40-6.40mgkg⁻¹ NH₄-N and 1.62-4.20mgkg⁻¹ NO₃-N. In comparison to plain land, non-cultivated land in hilly region contained two species *A. morrisi* and *P. corethrurus* having 18.6-36.8°C temperature, 7.4-7.9 pH, 5.04-18.20% moisture, 0.43-0.87dSm⁻¹ electrical conductivity, 0.27-0.45% organic carbon, 0.47-0.78% organic matter, 0.06-0.11% total nitrogen, 2.41-8.04 C/N ratio, 0.22-0.40mgkg⁻¹ potassium, 5.25-8.35mgkg⁻¹ phosphorus, 3.80-6.64mgkg⁻¹ NH₄-N and 2.00-5.00mgkg⁻¹ NO₃-N.

In garden land five species of earthworms viz., *A. morrisi*, *L. mauritii*, *M. posthuma*, *D. bolaui* and *O. beatrich* were recorded. Among these, plain area garden land had four earthworm species, but *A. morrisi* was not reported from garden land of plain area having 18.2-35.4°C temperature, 7.9-8.4 pH, 18.06-25.63% moisture, 0.25-0.86dSm⁻¹ electrical conductivity, 0.45-0.78% organic carbon, 0.78-1.35% organic matter, 0.08-0.15% total nitrogen, 4.02-5.51 C/N ratio, 0.32-0.58mgkg⁻¹ potassium, 8.05-10.40mgkg⁻¹ phosphorus, 5.79-9.90mgkg⁻¹ NH₄-N and 2.10-5.00mgkg⁻¹ NO₃-N. Whereas garden land system of hilly area showed the presence of two earthworm species (*A. morrisi* and *M. posthuma*) having 16.2-32.4°C temperature, 7.6-8.3 pH, 19.65-28.21% moisture, 0.25-0.61dSm⁻¹ electrical conductivity, 0.60-90% organic carbon, 1.04-1.56% organic matter, 0.10-0.14% total nitrogen, 6.12-6.43 C/N ratio, 0.46-0.56mgkg⁻¹ potassium, 9.56-11.38mgkg⁻¹ phosphorus, 6.65-9.60mgkg⁻¹ NH₄-N and 3.30-4.55mgkg⁻¹ NO₃-N. In contrast to garden, orchard land system had four earthworm species i.e. *D. bolaui*, *Gordiodrilus* sp., *L. mauritii* and *O. beatrich*. Two earthworm species (*D. bolaui* and *L. mauritii*) were present in both habitats. All the above four earthworm species were recorded from orchard land of plain area having 19.0-33.6°C temperature, 7.8-8.4 pH, 18.48-19.90% moisture, 0.33-0.68dSm⁻¹ electrical conductivity, 0.45-0.60% organic carbon, 0.78-1.04% organic matter, 0.08-0.09% total nitrogen, 5.84-6.59 C/N ratio, 0.28-0.48mgkg⁻¹ potassium, 7.53-10.55mgkg⁻¹ phosphorus, 4.46-5.87mgkg⁻¹ NH₄-N and 3.30-3.38 mgkg⁻¹ NO₃-N. Out of these four species, orchard land of hilly region showed two earthworm species (*D. bolaui* and *L. mauritii*) in soil having 18.0-31.6°C temperature, 7.2-7.8 pH, 18.48-21.95% moisture, 0.31-0.43dSm⁻¹ electrical conductivity, 0.48-0.72% organic carbon, 0.83-1.24% organic matter, 0.09-0.12% total nitrogen, 4.03-7.91 C/N ratio, 0.34-0.64mgkg⁻¹ potassium, 9.35-10.10mgkg⁻¹ phosphorus, 5.65-7.60mgkg⁻¹ NH₄-N and 3.90-4.50mgkg⁻¹ NO₃-N.

Total eight earthworm species viz., *A. morrisi*, *D. bolaui*, *Gordiodrilus* sp., *L. mauritii*, *H. houlleti*, *O. occidentalis*, *P. corethrurus* and *P. sansibaricus* were recorded from sewage system. *Gordiodrilus* sp., *D. bolaui* and *P. sansibaricus* were found in plain area having 21.0-35.0°C temperature, 7.4-8.1 pH, 25.63-35.87% moisture, 0.63-0.81dSm⁻¹ electric conductivity, 0.36-0.69% organic carbon, 0.62-1.19% organic matter, 0.06-0.07% total nitrogen, 6.43-9.86 C/N ratio, 0.55-0.92mgkg⁻¹ potassium, 7.88-16.10mgkg⁻¹ phosphorus, 4.00-7.00 mgkg⁻¹ NH₄-N and 2.18-4.38mgkg⁻¹ NO₃-N. While, in sewage system of hilly region, a total seven species of earthworm were observed excluding one earthworm species (*Gordiodrilus* sp.) found in plain sewage. The soil system of hilly region had 20.2-29.9°C temperature, 7.4-7.9 pH, 18.48-32.98% moisture, 0.26-0.67dSm⁻¹ electrical conductivity, 0.72-78% organic carbon, 1.24-1.55% organic matter, 0.08-0.09% total nitrogen, 7.91-10.13 C/N ratio, 0.68-1.38mgkg⁻¹ potassium, 9.30-29.90mgkg⁻¹ phosphorus, 4.50-7.15mgkg⁻¹ NH₄-N and 3.45-5.30mgkg⁻¹ NO₃-N. *A. morrisi*, *L. mauritii*, *M. konkanensis* and *P. corethrurus* were recorded from the forest land of this region. All the four species were observed from hilly region forest land.
although only two species L. mauritii and P. corethrurus were reported from plain area forest pedocosystem. Forest land of plain area had 19.8-36.6°C temperature, 7.7-8.7 pH, 14.29-25.00% moisture, 0.57-0.73dSm⁻¹ electrical conductivity, 0.42-60% organic carbon, 0.73-1.04% organic matter, 0.08-0.12% total nitrogen, 5.00-5.04 C/N ratio, 0.40-0.69mgkg⁻¹ potassium, 8.53-20.00mgkg⁻¹ phosphorus, 5.90-7.55 mgkg⁻¹ NH₄-N and 2.54-4.60mgkg⁻¹ NO₃-N. The hilly area forest land had 16.8-28.4°C temperature, 6.8-7.0 pH, 14.42-32.21% moisture, 0.38-0.65dSm⁻¹ electrical conductivity, 0.45-0.65% organic carbon, 0.78-1.14% organic matter, 0.11-0.13% total nitrogen, 5.24-7.40 C/N ratio, 0.58-0.87mgkg⁻¹ potassium, 18.00-25.20mgkg⁻¹ phosphorus, 6.80-7.40mgkg⁻¹ NH₄-N and 3.80-5.32mgkg⁻¹ NO₃-N.

In comparison to forest land, grass land pedocosystem had only three earthworms which were lowest in number found in any pedocosystems of this region. O. occidentalis and P. corethrurus were found in grass land of plain area having 21-33.8°C temperature, 7.4-8.6 pH, 14.9-15.74% moisture, 0.38-0.47dSm⁻¹ electrical conductivity, 0.96-1.20% organic carbon, 1.66-2.07% organic matter, 0.10-0.11% total nitrogen, 8.57-12.24 C/N ratio, 0.21-0.39mgkg⁻¹ potassium, 3.55-7.15mgkg⁻¹ phosphorus, 5.05-7.45mgkg⁻¹ NH₄-N and 3.85-4.80mgkg⁻¹ NO₃-N. Whereas, in hilly region O. occidentalis was replaced by L. mauritii in grass land having 18.02-30.2°C temperature, 7.5-8.4 pH, 10.13-26.90% moisture, 0.30-0.79dSm⁻¹ electrical conductivity, 0.48-1.50% organic carbon, 0.83-2.59% organic matter, 0.10-0.12% total nitrogen, 4.90-12.61 C/N ratio, 0.28-0.50mgkg⁻¹ potassium, 7.15-8.57mgkg⁻¹ phosphorus, 6.45-8.00mgkg⁻¹ NH₄-N and 3.60-4.00mgkg⁻¹ NO₃-N.

Table 9a. Occurrences of different species of earthworms in relation to physiochemical characteristics of soil in various pedocosystems of plain and hilly regions of Sirohi district of Rajasthan.

| Habits          | Cultivated (Samples were collected from wheat, mustard, maize castor, fenel, cereals, bamboo etc. crop fields) | Non-cultivated (Samples were collected from fallow lands and roadsides) | Garden (Samples were collected from parks, kitchen garden, temple garden and botanical garden under different plants.) | Orchard (Samples were collected from under the citrus, pomegranate, guava, papaya tree etc.) |
|-----------------|-------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
|                 | Moist. (%)                                                                                                 | Temp. (°C)                                                             | pH                                                                                                           |                                                                                              |
| Earthworm species* | 15.34-31.58                                                                                               | 8.1-8.9                                                                | 20.19-31.58                                                                                                 | 18.48-19.90                                                                                 |
| (dSm⁻¹)         | 0.26-0.91                                                                                                 | 3.25-7.80                                                              | 0.30-0.41                                                                                                   | 0.28-0.48                                                                                   |
| OC (%)          | 0.21-0.36                                                                                                 | 2.02-3.95                                                              | 6.62-9.85                                                                                                   | 0.34-0.64                                                                                   |
| OM (%)          | 0.30-0.62                                                                                                 | 0.08-0.11                                                              | 3.25-7.78                                                                                                   | 4.46-5.87                                                                                   |
| pH              | 8.1-8.9                                                                                                   | 2.86-3.95                                                              | 3.25-7.78                                                                                                   | 5.65-7.60                                                                                   |
| C: N Ratio      | 2.86-3.95                                                                                                 | 2.86-5.14                                                              | 3.25-7.78                                                                                                   | 5.65-7.60                                                                                   |
| K (mgkg⁻¹)      | 0.30-0.41                                                                                                 | 0.08-0.11                                                              | 2.86-3.95                                                                                                   | 5.65-7.60                                                                                   |
| P (mgkg⁻¹)      | 6.62-9.85                                                                                                 | 0.08-0.11                                                              | 2.86-3.95                                                                                                   | 5.65-7.60                                                                                   |
| NH₄-N (mgkg⁻¹)  | 3.25-7.78                                                                                                 | 0.08-0.11                                                              | 2.86-3.95                                                                                                   | 5.65-7.60                                                                                   |
| NO₃-N (mgkg⁻¹)  | 2.54-5.15                                                                                                 | 3.00-4.60                                                              | 2.86-3.95                                                                                                   | 5.65-7.60                                                                                   |

EC: Electrical conductivity; OC: Organic carbon; OM: Organic matter; N: Nitrogen; C: N ratio; Carbon: Nitrogen ratio; K: Potassium; P: Phosphorus, NH₄-N: Ammonia nitrogen; NO₃-N: Nitrate nitrogen.

(*): 1. A. morrisi, 2. D. bollai, 3. Gordiodrilus sp., 4. L. mauritii, 5. M. konkanensis, 6. M. houletti, 7. M. posthumus, 8. O. beatrix, 9. O. occidentalis, 10. P. corethrurus, 11. P. elongata, 12. P. sansibaricus.

Table 9b. Occurrences of different species of earthworm in relation to physicochemical characteristics of soil in various pedocosystems of plain and hilly regions of Sirohi district of Rajasthan.

| Habits          | Sewage (Samples were collected from kitchen, household sewage, civil drainage, near running water etc.) | Forest (Samples were collected from bamboo, Dhak, Dhaura, Amalts, Champa, Silver Oak, Eucalyptus tree etc.) | Grass land (Samples were collected from different grass lands) |
|-----------------|-------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| Earthworm species* | 2.3,12                                                                                                     | 2.3,12                                                                                                       | 9.10                                                                                                       |
| (dSm⁻¹)         | 12,64,9,10,12                                                                                             | 12,64,9,10,12                                                                                               | 4,10                                                                                                       |
| pH              | 7.4-8.1                                                                                                   | 7.4-8.1                                                                                                      | 7.4-8.1                                                                                                   |
| Moist. (%)      | 25.63-35.87                                                                                               | 18.48-32.98                                                                                                 | 18.28-24.2                                                                                               |
| EC (dSm⁻¹)      | 0.63-0.81                                                                                                 | 0.57-0.73                                                                                                   | 14.94-15.74                                                                                               |
| OC (%)          | 0.36-0.69                                                                                                 | 0.42-0.60                                                                                                   | 10.13-26.90                                                                                               |
| OM (%)          | 0.62-1.19                                                                                                 | 0.73-1.04                                                                                                   | 0.30-0.79                                                                                                 |
| Total N (%)     | 0.06-0.07                                                                                                 | 0.08-0.12                                                                                                   | 0.51-1.20                                                                                                 |
| C: N Ratio      | 6.43-9.86                                                                                                 | 5.00-5.34                                                                                                   | 0.48-1.50                                                                                                 |
| K (mgkg⁻¹)      | 0.55-0.92                                                                                                 | 0.40-0.69                                                                                                   | 0.28-0.48                                                                                                 |
| P (mgkg⁻¹)      | 7.88-16.10                                                                                                | 8.53-20.00                                                                                                  | 3.55-7.15                                                                                                 |
| NH₄-N (mgkg⁻¹)  | 4.00-7.00                                                                                                 | 7.45-7.15                                                                                                   | 7.15-8.57                                                                                                 |
| NO₃-N (mgkg⁻¹)  | 2.18-4.38                                                                                                 | 3.45-5.30                                                                                                   | 6.45-8.00                                                                                                 |

EC: Electrical conductivity; OC: Organic carbon; OM: Organic matter; N: Nitrogen; C: N ratio; carbon: nitrogen ration; K: Potassium; P: Phosphorus, NH₄-N: Ammonia nitrogen; NO₃-N: Nitrate nitrogen.

(*): 1. A. morrisi, 2. D. bollai, 3. Gordiodrilus sp., 4. L. mauritii, 5. M. konkanensis, 6. M. houletti, 7. M. posthumus, 8. O. beatrix, 9. O. occidentalis, 10. P. corethrurus, 11. P. elongata, 12. P. sansibaricus.
Table 10. Occurrences of different species of earthworms in relation to physiochemical characteristics of soil in various pedoecosystems of Sirohi district of Rajasthan.

| Habitat               | Cultivated (Samples were collected from wheat, mustard, maize castor, fennel, cereals, bazra etc. crop fields) | Non-cultivated (Samples were collected from fallow lands and road sides) | Garden (Samples were collected from parks, kitchen garden, temple garden and botanical garden under different plants.) | Orchard (Samples were collected from under the citrus, pomegranate, guava, papaya tree etc.) | Sewage (Sample were collected from kitchen, household sewage, civil drainage, near running water) | Forest (Samples were collected from bamboo, Dhak, Dhaura, Amaltas, Champa, Silver Oak, Eucalyptus tree etc.) | Grass land (Samples were collected from different grass lands) |
|-----------------------|-------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| Earthworm species*    | 1,2,4,7,8,10,11                                                                                             | 1,2,4,10                                                                 | 1,2,4,7,8                                                                                                                     | 2,3,4,8                                                                                                                      | 1,2,3,4,6,9,10,12                                                                                                                   | 1,4,5,10                                                                                                                     | 4,9,10                                                                                                                      |
| Temp. (°C)            | 16.8-36.4                                                                                                   | 18.6-37.8                                                                 | 16.2-35.4                                                                                                                   | 18.0-33.6                                                                                                                   | 20.2-35.0                                                                                                                      | 16.8-30.6                                                                                                                   | 18.2-33.8                                                                                                                   |
| pH                    | 7.2-8.9                                                                                                     | 7.4-8.4                                                                 | 7.6-8.4                                                                                                                      | 7.2-8.4                                                                                                                      | 7.4-8.1                                                                                                                      | 6.8-8.7                                                                                                                      | 7.4-8.6                                                                                                                      |
| Moist. (%)            | 15.34-31.58                                                                                                 | 5.04-32.28                                                                 | 18.06-28.21                                                                                                               | 18.48-21-95                                                                                                               | 18.48-35.87                                                                                                                   | 14.29-32.21                                                                                                               | 10.13-26.90                                                                                                               |
| EC (dSm⁻¹)            | 0.26-0.91                                                                                                   | 0.27-0.87                                                                 | 0.25-0.86                                                                                                                 | 0.31-0.68                                                                                                                   | 0.26-0.81                                                                                                                      | 0.38-0.73                                                                                                                   | 0.30-0.79                                                                                                                   |
| OC (%)                | 0.21-0.54                                                                                                   | 0.18-0.48                                                                 | 0.45-0.90                                                                                                                 | 0.45-0.72                                                                                                                   | 0.36-0.78                                                                                                                      | 0.42-0.66                                                                                                                   | 0.48-1.50                                                                                                                   |
| OM (%)                | 0.36-0.93                                                                                                   | 0.31-0.83                                                                 | 0.78-1.56                                                                                                                 | 0.78-1.24                                                                                                                   | 0.62-1.35                                                                                                                      | 0.73-1.14                                                                                                                   | 0.83-2.59                                                                                                                   |
| Total N (%)           | 0.06-0.13                                                                                                   | 0.06-0.11                                                                 | 0.08-0.15                                                                                                                 | 0.08-0.12                                                                                                                   | 0.06-0.09                                                                                                                      | 0.08-0.13                                                                                                                   | 0.10-0.12                                                                                                                   |
| C: N Ratio            | 2.86-5.14                                                                                                   | 2.41-8.57                                                                 | 4.02-6.43                                                                                                                 | 4.03-7.91                                                                                                                   | 6.43-10.13                                                                                                                      | 5.00-7.40                                                                                                                   | 4.90-12.61                                                                                                                  |
| K (mgkg⁻¹)            | 0.30-0.48                                                                                                   | 0.18-0.40                                                                 | 0.32-0.58                                                                                                                 | 0.28-0.64                                                                                                                   | 0.55-1.38                                                                                                                      | 0.40-0.87                                                                                                                   | 0.21-0.50                                                                                                                   |
| P (mgkg⁻¹)            | 6.26-9.85                                                                                                   | 4.28-8.35                                                                 | 8.05-11.38                                                                                                                | 7.53-10.55                                                                                                                 | 7.88-29.90                                                                                                                     | 8.53-25.20                                                                                                                  | 3.55-8.57                                                                                                                   |
| NH₄-N (mgkg⁻¹)        | 3.25-7.78                                                                                                   | 3.40-6.64                                                                 | 5.79-9.90                                                                                                                 | 4.46-7.60                                                                                                                   | 4.00-7.15                                                                                                                      | 5.90-7.55                                                                                                                   | 5.05-8.00                                                                                                                   |
| NO₃-N (mgkg⁻¹)        | 2.54-5.15                                                                                                   | 1.62-5.00                                                                 | 2.10-5.00                                                                                                                 | 3.30-4.50                                                                                                                   | 2.18-5.30                                                                                                                      | 2.54-3.52                                                                                                                   | 3.60-8.80                                                                                                                   |

EC: Electrical conductivity; OC: Organic carbon; OM: Organic matter; N: Nitrogen; C: N ratio; carbon: nitrogen ratio; K: Potassium; P: Phosphorus; NH₄-N: Ammonium nitrogen; NO₃-N: Nitrate nitrogen.

(*)-1. A. morrisi, 2. D. bolaui, 3. Gordiotridus sp., 4. L. mauritii, 5. M. konkanensis, 6. M. houlleti, 7. M. posthuma, 8. O. beatrix, 9. O. occidentalis, 10. P. corethrurus, 11. P. elongata, 12. P. sansibaricus.

3.5. Ecological Indices

Species diversity, Shannon index, dominance, richness, evenness, relative density and biomass of earthworms were calculated and described as follows.

3.5.1. Species Diversity and Shannon Diversity Index (H')

Annual species diversity index (H') of earthworm species in various pedoecosystem of plain and hilly area was calculated (Table 11). Minimum two species and maximum four species shared dominance in the different habitats of this region. Two species was recorded from each of the habitats like grass, cultivated and waste lands of plain and hilly areas. Similarly, garden and orchard land of hilly region, forest and sewage soil of plain region also shared two species. While the garden and orchard system of plain area and sewage pedoecosystem of hilly area had three species. In contrast, four species were recorded from forest land of hilly area. The species L. mauritii and A. morrisi were obtained from the waste land of plain area with an annual species diversity index of 0.692. Likewise, waste land of hilly region also shared two species (P. corethrurus and A. morrisi) with annual species diversity index of 0.690. A value of 0.656 species diversity index was calculated for grass land of hilly region with earthworm species comprising L. mauritii and P. corethrurus. In a similar way, two earthworm P. corethrurus and O. occidentalis were found in grass land of plain area with an annual diversity index of 0.580. Species diversity index in cultivated land of plain area was 0.690 and the species present in this habitat were L. mauritii and O. beatrix. Like hilly area agricultural land showed the occurrence of two worm viz., L. mauritii and A. morrisi having species diversity index of 0.649. All the above three habitats showed the shared dominance of two earthworm species.

Maximum number of four species was reported from hilly area forest land with highest annual species diversity index of 1.27 and the species found in this habitat were L. mauritii, M. konkanensis, A. morrisi and P. corethrurus. In contrast the plain area forest land contained only two species (L. mauritii, P. corethrurus) with 0.676 species diversity index. Three species was observed in each of the habitats viz., garden and orchard land of plain area and sewage land of hilly area. Second highest annual diversity index value 1.07 was recorded for garden land of plain area with the earthworm species L. mauritii, O. beatrix and D. bolaui. A value of 0.947 species diversity index obtained for orchard land of plain area with species comprising L. mauritii, Gordiotridus sp. and D. bolaui. Correspondingly, sewage system of hilly area also showed the presence of three species O. occidentalis, P. sansibaricus and L. mauritii with 0.901 species diversity index. On the contrary, garden and orchard land of hilly region and sewage land of plain area exhibited two earthworm species having 0.644 (A. morrisi and M. posthuma), 0.640 (L. mauritii and D. bolaui) and 0.692 (D. bolaui and Gordiotridus sp.) annual species diversity indices respectively (Table 11).

3.5.2. Species Dominance, Richness and Evenness

Species dominance indices (C) in cultivated, non-cultivated and grass land of plain areas were 0.53, 0.51 and 0.73 respectively (Table 11). The species dominance indices of cultivated (0.64), non-cultivated (0.53) and grass land (0.63) of hilly region were also calculated.
Similarly, the species dominance indices (0.65 and 0.66) were calculated for garden and orchard system of hilly region. Whereas 0.52 value of species dominance indices was computed for sewage soil of plain region. It’s shared by dominance of two species in each of these habitats. Three species were recorded from garden (plain area), orchard (plain area) and sewage land (hilly region) with 0.42, 0.59 and 0.59 species dominance indices respectively. These values indicated shared dominance of three species. In the forest land of plain area there was two species sharing species dominance index of 0.59. On the other hand, species dominance index in hilly forest land was 0.39 which showed shared dominance of four species. Species richness, evenness and effective number were also calculated (Table 11). Species richness was highest for forest land of hilly region (0.465) and lowest for sewage soil of plain area (0.160). Effective number were also calculated (Table 11). Species richness, evenness and effective number were also calculated (Table 11). Species richness was highest for forest land of hilly region (0.465) and lowest for sewage soil of plain region (0.999).

3.5.3. Relative Density and Biomass

Data on relative density (RD) and relative biomass (RB) are shown in Table 12. The earthworm species *L. mauritii* (RD 59.32%, RB 75.40%) dominated in agricultural land followed by *O. beatrix* (RD 40.68%, RB 24.60%). *L. mauritii* was again leading species in wasteland with a relative density of 52% and relative biomass of 53.87%. *A. morrisi* contributed 48% of relative density and 46.13% relative biomass in this habitat. In grass land *P. corethrurus* presented 55.81% RD and 53.29% RB. It was dominant over *L. mauritii* (RD 44.19%, RB 46.71%). *D. bolaui* was dominant species in garden and orchard land with relative density of 43.18% and 59.72% respectively. Whereas *O. occidentalis* was dominant over *P. sansibaricus* (RD 33.69%) and *L. mauritii* (RD 9.94%) in sewage soil with relative density of 59.37%. In forest land relative density of *L. mauritii* (RD 39.75%) was dominant over *M. konkanensis* (RD 31.64%), *A. morrisi* (RD 17.65%) and *P. corethrurus* (RD 10.97%). However, based on earthworm biomass, *L. mauritii*, *M. konkanensis*, *A. morrisi* and *P. corethrurus* contributed 37.65%, 37.46%, 15.50% and 9.39% in forest land respectively.

### Table 11. Ecological indices for earthworm fauna in Plain and hilly region of Sirohi district of Rajasthan

| Habitat       | Area       | Number of Species (S) | Simpson Diversity Index (D) | Shannon Diversity Index (H') | Dominance Index (C) | Species Richness (d) | Evenness Index (e) | Effective Number of Species |
|---------------|------------|-----------------------|-----------------------------|-------------------------------|--------------------|---------------------|---------------------|-----------------------------|
| Agricultural land | Plain  | 2                      | 0.5008                      | 0.6904                       | 0.5373             | 0.1805              | 0.996               | 1.9945                      |
|                | Hill      | 2                      | 0.5416                      | 0.6492                       | 0.6471             | 0.1784              | 0.9367              | 1.9140                      |
| Waste land     | Plain  | 2                      | 0.4973                      | 0.6929                       | 0.5116             | 0.1943              | 0.9996              | 1.9995                      |
|                | Hill      | 2                      | 0.4994                      | 0.6909                       | 0.5333             | 0.1926              | 0.9968              | 1.9955                      |
| Garden land    | Plain  | 3                      | 0.3463                      | 1.0771                       | 0.4289             | 0.3347              | 0.9805              | 2.9358                      |
|                | Hill      | 2                      | 0.5468                      | 0.6441                       | 0.6553             | 0.1732              | 0.9293              | 1.9042                      |
| Orchard land   | Plain  | 3                      | 0.4392                      | 0.9473                       | 0.5972             | 0.3147              | 0.8623              | 2.5787                      |
|                | Hill      | 2                      | 0.5506                      | 0.6405                       | 0.6608             | 0.1668              | 0.924               | 1.8974                      |
| Sewage soil    | Plain  | 2                      | 0.4999                      | 0.6922                       | 0.5216             | 0.1604              | 0.9987              | 1.9981                      |
|                | Hill      | 3                      | 0.4558                      | 0.9017                       | 0.5939             | 0.3058              | 0.8208              | 2.4647                      |
| Forest land    | Plain  | 2                      | 0.5148                      | 0.6765                       | 0.5900             | 0.1768              | 0.976               | 1.9669                      |
|                | Hill      | 4                      | 0.302                       | 1.275                        | 0.3994             | 0.4659              | 0.9196              | 3.5930                      |
| Grass land     | Plain  | 2                      | 0.6069                      | 0.5809                       | 0.7324             | 0.1703              | 0.838               | 1.7876                      |
|                | Hill      | 2                      | 0.534                       | 0.6565                       | 0.6346             | 0.1874              | 0.9471              | 1.9280                      |

### Table 12. Relative density (RD%), relative biomass (RB%) and relative frequency (RF%) of few earthworm species in seven different habitats of Sirohi district of Rajasthan

| Earthworm species | Cultivated field | Non-cultivated field | Garden land | Orchard land | Sewage soil | Forest land | Grass land |
|-------------------|------------------|----------------------|-------------|--------------|-------------|-------------|------------|
|                   | RD | RB | RF | RD | RB | RF | RD | RB | RF | RD | RB | RF | RD | RB | RF | RD | RB | RF |
| *P. corethrurus*   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| *A. morrisi*      | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
|                   | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| *L. mauritii*     | 59.32 | 75.40 | 100 | 52.00 | 53.87 | 100 | 30.56 | 66.76 | 100 | 16.67 | 35.79 | 40 | 9.94 | 25.15 | 40 | 39.75 | 37.65 | 100 | 44.19 | 46.71 | 100 |
| *M. konkanensis*  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| *P. sansibaricus* | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| *D. bolaui*       | -  | -  | -  | -  | -  | -  | -  | -  | -  | 43.18 | 5.93 | 80 | 59.72 | 61.02 | 100 | -  | -  | -  | -  | -  |
| *O. beatrix*      | 40.68 | 24.60 | 80 | -  | -  | -  | 26.26 | 27.30 | 100 | 23.61 | 3.19 | 100 | -  | -  | -  | -  | -  | -  | -  | -  |
| *O. occidentalis* | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | 59.37 | 4.72 | 60 | -  | -  | -  | -  | -  | -  | -  | -  |

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4. Discussion

4.1. Biodiversity

Various sites of both plain and hilly area of Sirohi district of Rajasthan showed the occurrence of twelve species earthworms belonging to four families (Table 2, Figure 3A). Few workers have also reported some earthworm species from Rajasthan [23,24,67,80]. Suthar [81] reported nine species of earthworm belonging to five families from western arid and semi-arid region of Rajasthan. Out of twelve earthworm species of Sirohi district, only three species (L. mauriti, P. sansibaricus, O. beatrrix) were native peregrine and remaining nine were exotic peregrine. Distribution of earthworms may be related to environmental conditions [82]. Julka [83] stated that there are no endemic earthworms in Rajasthan. It is known that occurrence of exotic species was often dominated in native [84, 85]. Ten earthworm species were found in Aburoad tehsil including hilly parts of Mount Abu (Table 2, Figure 3A). Among these nine species were obtained from hilly region (Table 4, Figure 3B). The earthworm species M. houlleti and M. konkanensis were observed in hilly area (Mount Abu) only, while P. elongata, O. occidentalis and O. beatrrix were found in plain area and were absent in hilly habitats (Table 4, Figure 3B). The earthworm species diversity in Mount Abu was higher than another region. It may be due to a good vegetation and climatic condition. From one vegetation type to the other, earthworm species composition may change [86]. This area was also well connected with the other places of country, so transportation and tourism are more which facilitated rapid and easy carrying of earthworms from one to another place. The distribution of earthworms in Pindwara tehsil was poor as compared to the other part of the district. It may be due to somewhat hard physiochemical condition of lands. Earthworm diversity and distribution pattern are generally governed by a variety of biotic and abiotic factors such as soil properties, surface litter, vegetation type and its dynamics, land use pattern, local or regional climate and pressure of human activities [81,87,88,89]. Due to their relationship to soil ecosystem function, earthworm population structure may be influenced by a change in vegetation and soil characteristics, as well as biotic and abiotic interactions [86,90,91,92]. Among the abiotic factors, soil physiochemical characteristics viz., soil moisture, organic carbon, total nitrogen and temperature played important role. However, in surveyed area no earthworm was recorded from soil having less than 5.71% soil moisture and temperature more than 37.8°C (Table 1).

4.2. Ecological Categories

Eco-morphological characteristics and ecological categories of earthworms of Sirohi district of Rajasthan are given in Table 3. Among the recorded species D. bolaui, L. mauriti, M. konkanensis, O. occidentalis, O. beatrrix, Gordiodrilus sp. and P. elongata did not show any pigmentation and defined as colourless. Whereas P. corethrurus was pale brown in colour and A. morrisi was reddish brown in appearance. The earthworm M. posthuma was dark brown but M. houlleti was reddish in colour. However, P. sansibaricus was dark purple in appearance. Colouration in worms indicated the presence of pigments in their body. The body pigmentation in earthworms is to protect them from ultraviolet radiation. These characteristics features of colouration in earthworms of arid region of Rajasthan have also been reported by Tripathi and Bhardwaj [23]. Different species of earthworms occupy different ecological niches. Based on their feeding and burrowing strategies, they have been divided into three ecological categories viz., epigeic, anecic, and endogeic [93,67,94,95,96]. The species P. corethrurus, M. konkanensis, O. occidentalis and O. beatrrix were endogeic. While P. sansibaricus, D. bolaui and Gordiodrilus sp. were epigeic. M. posthuma and M. houlleti were endo-anecic. However, A. morrisi was epi-anecic. On the other hand, L. mauriti and P. elongata were purely anecic species of earthworms reported from Sirohi. This showed that the soil layer of more than 30 cm deep was not suitable for propagation of earthworms. The earthworm fauna of Sirohi district of Rajasthan are endogeic, epigeic, endo-anecic, epi-anecic and anecic in nature. This type of categorical identification on ecological basis may help in identifying the suitable species for land use management and ecosystem of degraded land. Functional attribute and ecological strategy of different earthworm species need to be worked out to optimize the contribution of earthworms to ecosystem services and liability of agro-ecosystems.

4.3. Earthworm Composition and Density

Table 5a, Table 5b, Table 7 and Figure 4A-G represent the qualitative composition and average annual density of earthworms in various habitats of plain and hilly region of Sirohi district of Rajasthan. The combined qualitative composition and average annual density of earthworms in various habitats of Sirohi region were illustrated in Table 6 and Table 8. Here the total twelve identified earthworm species belonged to four families. Out of these, three earthworms (viz., M. konkanensis, M. houlleti, Gordiodrilus sp.) were recorded for the first time from Rajasthan. A few earthworm species such as L. mauriti, A. morrisi, P. corethrurus and D. bolaui showed their presence in most of the localities, while P. elongata, M. houlleti, Gordiodrilus sp. and M. konkanensis were restricted to a particular locality in this region. In the same way, the earthworm species composition and abundance in different habitats have been documented [23,25,36,41,81,97]. The earthworm species L. mauriti was abundantly found in forest land. D. bolaui was abundantly recorded from orchard and sewage soils, while O. occidentalis was abundant in sewage and grass lands. Similarly, Gordiodrilus sp. was abundantly present in sewage systems. In contrast, the cultivated, non-cultivated and garden lands showed moderate and poor presence of earthworm species. The earthworm L. mauriti was commonly recorded from all types of pedoecosystems. P. corethrurus, D. bolaui and A. morrisi were present in all habitats except two (Table 8). However, M. houlleti and P. sansibaricus were obtained only from sewage soil. Likewise, M. konkanensis and P. elongata were restricted to forest and cultivated land respectively. The presence
and absence of earthworm species in a particular habitat showed the species-specific habitat preferences in different pedoecosystems. It has been observed that stable ecosystem has high species diversity and density as compared to unstable one [98,99,100]. Seven species of earthworms were recorded from cultivated lands. Among these six species were from plain and two species from hilly parts in which one was commonly found in both areas (Table 7). Diversity of earthworm was higher in agricultural land of plain area. It may be due to advanced farming system or nutrient enrichment of agricultural lands. Bisht et al. [101] reported population dynamics of six earthworm species in cultivated soil of central Himalaya tarai region. Maximum numbers of earthworms were recorded from the places where farmers followed integrated farming [102].

Non-cultivated lands harboured four earthworm species (three from plain and two from hilly region). Here one species was commonly recorded from both the places. Five earthworm species exhibited their presence in garden pedoecosystem, in which, four species were recorded from plain and two from hilly parts, but one species was commonly found in both regions of garden lands. Although orchard and forest lands of plain area presented four earthworms, in which two was common in both parts. Lalthanzara et al. [103] found that the earthworm density and community structure were different in various agroforestry systems of Mizoram, India. Rathinamala et al. [104] have analyzed and found that the population of earthworm was more in grass and non-cultivated lands than chemically fertilized land. Occurrences of five earthworm species in agricultural and plantation fields of Rajapalayam, Tamilnadu has been documented [60]. Eight earthworm species were recorded from sewage systems of this region. Out of these seven species were identified from sewage of hilly area and three from plain area sewage. Here two earthworm species were commonly found in sewage system of both areas. In contrast, grassland of plain and hilly region harboured three earthworm species; two were common in each area and one was different in grassland of plain area. Sewage system contained more diversity than other systems. It may be due to presence of high organic and nitrogen in habitat [23]. Verma et al. [105] recorded the inhabitance of 10 earthworm species in eastern Uttar Pradesh (U.P.) and their inhabitance changed according to habitats. Kumar and Singh [106] reported the earthworm population from cultivated, garden and grasslands of Gorakhpur district of U.P. Bairi et al. [63] studied the variation in density of earthworm in bamboo, teak and tamarind grass lands. Singh et al. [41] observed that abiotic factors and land use patterns of the soil were responsible for distribution of earthworm in various fields.

Like present observations the species composition of earthworms of grassland, cultivated and forest soils have been described [65,107,108,109]. Diversity, distribution and abundance of ten earthworms belonging to six families have been recorded from Pondicherry [25]. Populations of twenty species of earthworms belonging to five families have been studied in Tripura [26]. Diversity and distribution of seven species of earthworms in forest ecosystem of Imphal have been described [32]. Mohan et al. [33] observed the distribution and relative abundance of six earthworm species in Amritsar. Rai and Nath [97] documented the distribution of twenty-two earthworm species in different habitats of Uttar Pradesh. Dissimilarity in earthworm diversity and density of twelve species from different Indian botanical gardens of Howrah has been reported [110]. Goswami [45] recorded eight species of earthworm from Satyajit Ray Film Television Institute, Kolkata. The highest abundance with greatest diversity was found in residential areas, though the lowest abundance was found in the bank of water bodies and lowest diversity in the grassland habitat. The properties of soil also play a significant role in changing earthworm diversity indices [47].

4.4. Habitat Relationship

Earthworms have been recorded from different habitats of hilly and plain areas. Maximum earthworm density and diversity in soil suggested the suitability of a particular area for earthworms. Among the recorded species *A. morrisi, L. mauritii, P. corethrurus,* and *D. bolai* were found in most of the habitats of the studied areas (Table 9a, Table 9b, Table 10). It showed a wide range of tolerance to such climatic conditions. Whereas some showed restricted distribution patterns like *M. houleti* and *P. sansibaricus* in sewage and *M. konkanensis* in forest soils (Table 5a, Table 5b). The present result may be supported by work of Tripathi and Bhardwaj [23,24] who described common occurrence of earthworm species in different habitats of arid region of Rajasthan. It is also supported by the findings of Sharma and Bhardwaj [36] who explained the earthworm diversity of Trans-Gangetic habitats of Haryana. In the studied areas, cultivated, garden, orchard, forest and sewage soils showed better condition as compared to other habitats. The physico-chemical characteristics of the soil such as pH, electrical conductivity, total nitrogen and organic carbon, availability of food such as leaf litter, dung and garbage, climatic factors of the study area such as soil moisture, soil temperature, humidity and rainfall, and reproductive potential of the earthworm species play an important role in the horizontal distribution of earthworms. It has been reported that the occurrence of earthworm is related to physiochemical conditions of the soil i.e., temperature, moisture, pH, C/N ratio etc. These may affect the diversity, density and abundance of earthworm [10]. Most of the earthworm species prefer soil with temperature of 10-35°C, moisture of 12-45%, pH about 7 and C/N ratio 2-18 [49,111]. Suitable temperature, moisture, aerobicity etc. of the topsoil create favourable microclimatic conditions for the soil dwelling earthworms [26]. Soil biological data on the occurrence and abundance of earthworms were analyzed with respect to their distribution and relation to site (habitat type, land use) and soil properties (pH, texture, organic matter) [112].

The occurrence of high diversity and abundance of earthworm in sewage soil as compared to other pedoecosystems may be due to presence of higher organic carbon and nitrogen in sewage system. It showed that earthworms prefer to live in soil ecosystems rich in organic matter and nitrogen. The present observations agree to the findings of other workers [23,28,113,114]. Various ecological parameters play a vital role in
regulating the distribution of earthworms [115]. Many workers have also studied the habitat preference of various earthworm species [23,25,110,116,117]. In contrast grass land and non-cultivated fields showed lowest density and diversity (Table 6). It may be due to unfavorable soil condition such as moisture, C/N ratio and temperature. The soil temperature plays an important role in the maintenance of earthworm population in an ecosystem and there is a negative correlation of soil temperature to earthworm population [118,119]. Soil moisture contributes a major share in the distribution and occurrence of various earthworm species [120,121]. Earthworm activity and population are determined essentially by the moisture content of the soil and that soil moisture and population estimates are positively correlated [113]. The organic matter of soil greatly influences the distribution of earthworms and soils with low organic matter generally do not support earthworm population [48,122]. Increase in organic matter of semi-arid agricultural soils in Egypt was associated with increased number and biomass of earthworms [123]. Some of the reports support qualitative dependence of earthworm population on soil organic matter [54,124,125]. The composition and texture of soil have a great influence on the distribution and population structure of earthworms [126]. Baker et al. [127] have also reported that differences in various chemical properties, viz. organic C, N, P, K etc. are responsible for the distribution and abundance of earthworms in soil of an area.

The present investigation suggests that various climatic and edaphic factors are responsible for diversity, distribution and abundance of earthworms in different habitats. Similar conclusions have been drawn for the species composition of earthworms in grass land, cultivated and forest soils [46,65,128]. The earthworm diversity and distribution enhance the biological diversity, soil environment and fertility. Hence it very important to study earthworm populations in a variety of habitats at the same time of a year, so that it is easy to assess precisely which habitats can support large earthworm populations [120]. The species diversity, ecomorphological characteristics, qualitative compositions, species-habitat relationship of earthworm exhibited remarkable differences in hilly and plain areas. This may be attributed to the differences in soil system. The described species may be differentially adopted for improving pedoecosystem, amelioration and restoration of soil environment in hilly and plain areas.

4.5. Species Diversity Indices

Most earthworm diversity reports showed the presence of two to five species at any single location [50,129]. Sirohi region, with earthworm communities having 2 to 4 species, exhibited the similar diversity. Soil types can also affect earthworm population [50]. Earthworm richness depends on soil characteristics. Shannon-Weiner diversity index ($H'$) and Margalef’s species richness index ($d$) were recorded highest in forest land area of hilly region ($H'$=1.27, $d$=0.46) followed by garden land of plain area ($H'$=1.07, $d$=0.33) and minimum diversity index ($H'$=0.58) was in grass land of plain area. While lowest species richness ($d$=0.16) of earthworms was in sewage soil of plain area. Maximum species evenness (equitability index) was recorded for waste land of plain area and minimum in sewage system of hilly region as shown in Table 11. The value of evenness index was closer to the one means more even is the distribution of species. Higher values of these indices indicated greater species diversity. Higher values of species diversity and species richness in forest pedoecosystem of hilly region showed abundant food and suitable physicochemical conditions as compared to other sites [130,131]. Differences between the earthworm communities in different localities indicate that environmental heterogeneity is important in promoting earthworm diversity (beta diversity), as it has been described by Fragoso and Lavelle [132] in the forests of Mexico. It is so obvious that the suitable physicochemical factors as compared to other sites enhance the values of species diversity and richness at habitat.

Najar and Khan [29] reported highest diversity and evenness index in vegetable garden soil. Haokip and Singh [32] calculated maximum value of species diversity for different forest ecosystems of Imphal-West, Manipur. Sharma and Bhardwaj [36] have determined different species indices in Trans- Gangetic habitats of Haryana. Goswami and Mondal [40] have also recorded 3-4 species with species richness in different habitats of south 24 parganas district in West Bengal. In similar way, ecological indices in different habitats have been investigated [41]. However, species dominance index was highest for those pedoecosystem who had lowest species diversity index and vice-versa. On other hand effective number of species was highest (3.59) in forest pedoecosystems and lowest (1.78) in grass land of plain area (Table 11). Jost [133] proposed that diversity values be converted into equivalent or effective numbers of species (also known as Hill numbers), which is the number of equally abundant species necessary to produce the observed value of diversity (an analogue to the concept of effective population size in genetics). Relative density, relative biomass and relative frequency of earthworm in India have been reported only for a very few ecosystems. In Sirohi district relative density, relative biomass and relative frequency of few earthworms in different habitats were studied (Table 12). Among these species L. mauritii with relative density of 59.32%, 52% and 39.75% was the most dominant species in cultivated, non-cultivated and forest lands respectively. Dominance of D. bolitii was obtained in garden and orchard land with relative density of 43.18% and 59.72% respectively, while in sewage soil O. occidentalis was dominant with relative density of 59.37%. P. corethrurus (RD=55.81%) dominated in grass land pedoecosystem. More or less similar results were obtained in different habitats of Jodhpur district of Rajasthan [23].

5. Conclusion

The vegetation cover, intensive agriculture practices, favorable climatic conditions and average rainfall system indorse successful colonization of earthworm communities in a particular area. Different earthworm species showed an asymmetrical dispersal in some restricted sites due to species-specific habitat relationship.
Relative density, frequency and species diversity of earthworm resources vary in different habitats of plain and hilly areas. Findings may be utilized for eco-restoration of degraded land on self-sustainable basis.

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