

Review

Understanding cactus pear status for improved ecosystem services in northern Ethiopia

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Abstract

Prickly pear (*Opuntia ficus-indica*) is a multipurpose plant in drylands. The objective of this study was to synthesize the livelihood benefits, survival threats and management of cactus pear in Tigray (Ethiopia). Metadata were generated from 63 available articles. Accidental interviews ($n=35$) and frequent field observations were also used to substantiate the metadata. Descriptive statistics and descriptions were used to analyze the data. In the meta-analysis, cactus is a viable biological measure to maintain soil quality and moisture, as it has high water use efficiency. In addition, cactus provides an average yield of 16.20 ± 8.33 tons fruits per ha. The plant is also a source of income and a live fence in low rainfall sites. The dryland plant has bridged the food and forage gaps. The cochineal insect, which eats only cactus, was introduced for a dyeing business. However, mismanagement of the insects invaded vast cactus-rich sites at an alarming rate. The infested areas increased from 17 villages in 2011 to 139 villages in 2018 with an average damage of 3,890 ha of cactus per year. The study highlights that research institutions and Tigray government have failed to address the cochineal infestation for about 15 years. Consequently, the poor farmers received neither cactus benefits from harvesting carmine nor other ecosystem services. Therefore, we suggest that integrated pest management efforts and expansion of cactus plantations along the western escarpment in the Rift Valley improve food availability and defend the landscape against the expansion of desertification in northern Ethiopia.

Keywords Cactus · Cochineal · Drought · Income · Pest management · Rehabilitation

1 Introduction

Opuntia ficus-indica is a common wild edible fruit tree and shrub species in the drylands [1, 2]. Prickly pear (hereafter written as cactus) is a succulent shrub or tree species. Biogeographic analysis indicates that drylands have a suitable niche for cactus growth [3]. The cactus grows on highly degraded hillsides, and it survives on mountain tips, inaccessible cliffs and mountains [4, 5]. It is also reported that cactus grows in diverse climatic conditions from moist to water-stressed areas. Furthermore, cactus grows in moisture deficient sites [6, 7]. Unlike other staple crops, therefore, the cactus plant is reliable insurance for poor farmers that grow in a difficult environment [8].

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Cactus offers livelihood benefits and ecosystem services. The ecosystem services of cacti are important resources and processes that benefit people. It provides provisioning services (food for humans, feed for livestock and medicines), supporting ecosystem services (providing wildlife with food, pollen, habitat, and shelter), regulating services (controlling soil erosion, providing material for mulching, sequestering carbon) and cultural services (e.g., live fences) [5, 9, 10]. It is also an important livelihood asset for poor farmers in degraded lands [11–14].

[5] highlighted that cultivation of cactus is in South America, North America, southern European countries, Africa and Middle Eastern countries. The cactus plant is endemic to Mexico [8]. In view of this, Mexico is the largest producer of cactus (45%), followed by Italy (12.2%) and South Africa [15].

In response to famine due to frequent droughts and wars, a Catholic missionary brought cactus cladodes to eastern Tigray, northern Ethiopia in 1848 [16]. Subsequently, the cactus has propagated to the eastern and southern parts of Tigray over time [17]. The vernacular name of the cactus is “Beles” [18]. In many areas, cactus has been grown for hedging, fodder, and edible fruits while taking advantage of its drought tolerance. An extensive cactus distribution exists in Tigray [19, 20]. It was also reported that cactus covers an area of 355,242 ha, of which 30,352 ha are in the form of cultivation in Tigray alone [20].

Cactus has been underutilized in Tigray [20], despite its immense livelihood benefits [4]. As a crop plant, its fruits, cladodes and flowers have outstanding value in the region [22]. A prickly pear cochineal (*Dactylopius coccus* Costa, hereafter shortened as cochineal) was introduced from South Africa to Tigray region in April 2003 for carmine cochineal production [23]. Initially, a good harvest of the cochineal yields was collected from the farmers and exported to abroad. For example, 984 dollars could be generated per ha [24]. It had an outstanding economic value in the cactus-rich areas.

However, it was reported that the cochineal became an invasive pest of cactus mainly in 2009 in cactus-rich areas [24]. The carmine cochineal has become a devastating insect pest [25]. There have been scientific studies about the livelihood benefits, survival threats and management of cactus pear since the introduction of the insect. The findings of these studies are scattered over time and space. Such scientific “dots” of knowledge did not bring the desired solution. Hence, bringing available evidence together provides sufficient knowledge for a better response to emerging challenges, including pest infestation [26].

Reviewing the state-of-the-art knowledge and performing meta-analysis is one of the best ways to determine the condition of the cactus. With this background, the purpose of this study was to investigate the conditions of cactus and cochineal infestation, and their implications for livelihood in the arid and semiarid Tigray region of Ethiopia through meta-analysis.

A comprehensive review of scientific studies was organized to address the following research questions: (1) What are the ecosystem services of cactus plants in relation to the livelihoods of farmers? (2) What are the emerging challenges threatening the cactus physical distribution? (3) What kinds of management practices are on the ground, and if they are insufficient, what could be done to sustain cactus status for livelihoods?

The research findings of this study help to provide evidence of the livelihood benefits, survival threats, and management interventions of cactus for practitioners, researchers and policymakers to enhance ecosystem services for the better livelihoods of communities. Furthermore, this synthesis updates the global cactus literature in favor of sustainable development goals in a challenging environment.

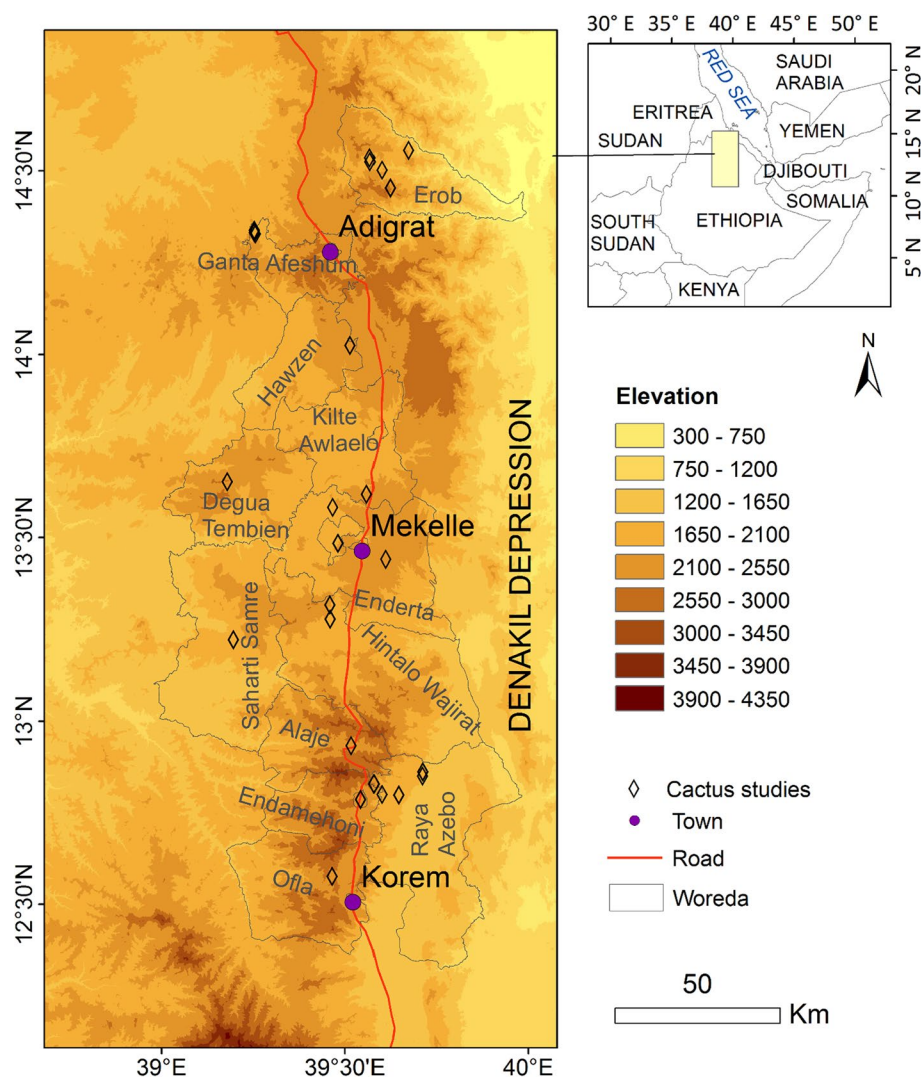
2 Methods and materials

2.1 Environmental setting

The critical review was carried out in Tigray, northern Ethiopia (Fig. 1). The region is found between 12°15' and 14°57' N and 36°27' and 39°59' E.

The altitude ranges between 500 and 4000 m a.s.l. It covers 53,386 km², of which 20% is under crop cultivation. The presence of highlands, plateaus, and valleys intermingled with flat lands and low hills resulted in distinctive agroecological zones. The climate of the region is 39% semiarid (*Kolla*), 49% warm temperate (*Woina Dega*) and 12% temperate (*Dega*). In the cactus-dominated western escarpment, the annual rainfall varies between 300 and 600 mm, with a mean annual rainfall of 562 mm [27]. Furthermore, the temperature reaches 40 °C; moisture deficit and droughts have been frequent problems for plant growth [27].

Fig. 1 The location of the case studies



The major soil types are Cambisols, Rendzinas, Lithosols, Acrisols, Fluvisols, Luvisols, Regosols and Nitisols [28]. Moreover, Precambrian metamorphic rocks, late Paleozoic to Mesozoic marine and continental sediments, and Cenozoic basic and felsic volcanic, volcano-sedimentary, and clastic rocks are the major rocks in the study area [29].

Croplands, exclosures, remnant forests, villages, and built-up areas are the dominant land use types in the study area where the farming system consists of crop and animal production. Moreover, rocky and bare steep slopes cover 12% of the entire area. Widespread soil erosion and droughts cause a reduction in food security [30].

The western escarpment that extends through north Wollo-Raya graben-Wejerat-Enderta-Erob-Eritrea has been a cactus-rich geographical belt (Fig. 1). In this geographical area, the poor and better off farmers have private cactus land at their homesteads and communal areas [31]. Based on our field experience in the region, cactus flowers from January to February every year, and fruit setting starts in April. Next, the fruits are harvested from May to September.

2.2 Methods

2.2.1 Data acquisition

A critical review of cactus studies was conducted to understand and document historical cactus conditions and their implications for the livelihood of the community in the northwestern section of marginal areas of the Rift Valley in Tigray. In this context, scientific articles, reports, international proceedings, and academic theses were reviewed for this study. In line with [32], Google Scholar, Web of Science, and ScienceDirect were used to extract the evidence. The search time scale for literature

was up to March 27 2022. After March 2022, new publications were used for discussion of the evidence. The search variables were “cactus and benefit”, “cactus threat”, “cactus and climate”, “cactus and land use”, “cochineal infestation and measure”, “cochineal and control”, “cactus and Tigray”, “cactus and “northern Ethiopia”.

We computed the economic benefits of cactus (Table 1). The number of fruits per plant (N_f) for 13 locally grown cactus cultivars as well as the number of cactus plants per ha (N_{ha}) (622 plants per ha for upright type cultivars and 950 plants per ha for bushy types) were adopted to compute the economic benefits of cactus plantations in the study area [33].

On-sites, the market price of cactus fruit was collected from local markets. As the price was nearly similar, and fixed by the sellers, 14 producers were also accidentally interviewed in August 2022 for validation of the fruit price. Accordingly, the price per piece (P_u) was \$ 0.0566 (1\$ = 53 Ethiopian BIRR). We also considered the total area of cactus covers (A_{tot}) to be 35,000 ha [17]. Moreover, we considered the forage productivity (P_c) of cactus to be 20 tons dry matter per ha year [12].

Based on the findings of [33], we compiled the temporal wasted opportunity (missed benefits) of the destroyed cactus due to the pest. We also collected the total invested area (A_f), cochineal productivity (P_c) and cochineal harvest frequency in a year (H_f). As highlighted above, the present market price (P_m) was collected to compute the annual income of cochineal yields would have generated (I_{ac}). Furthermore, we collected on-site information; cochineal business beneficiaries (smallholder farmers along the cactus-rich sites) stated that they harvested fresh dried cochineal yield 3 times a year [24]. Moreover, [24] suggested that cochineal productivity was about 246 kg per ha area was sold 4 \$ per kg.

Furthermore, this work benefited from repeated field observations in the cochineal infested cactus sites in Hawzien, Edaghamus, Raya Azebo and Enderta to triangulate extracted metadata, literature evidence (Fig. 1) between 2013 and 2022 in the cochineal affected districts. During the transect walks, random interviews (n = 21) were conducted with local farmers to obtain their understanding of the impacts of the insect infestation on their cactus [31].

2.2.2 Data processing and analysis

We computed annual cactus fruit income. Based on the metadata presented above, the total annual income (I_{tot}) from fruits of cactus was computed as follows:

$$I_{tot} = N_f * P_u * N_{ha} \quad (1)$$

Moreover, the total annual forage of cactus (F_{tot}) was determined as follows:

$$F_{tot} = A_{tot} * P_c \quad (2)$$

Table 1 Calculation of economic benefits of cactus in Tigray

Vernacular name	English meaning	Average # of fruits per plant	Fruit weight (g)	Total # fruits in ha	Productivity (tons/ha)
<i>Neitsi</i>	White	423	114.62	263106	30.15
<i>Gerao</i>	Sweet	317.34	144.41	197385.5	28.44
<i>Naharisa</i>	Causes vomiting	278.33	146.59	173121.3	25.37
<i>Orgufa</i>	Falls down early	322	110.99	200284	22.2
<i>Suluhna</i>	Spineless	224	142.36	139328	19.88
<i>Ameudegaadobelssa</i>	White colored	161.33	97.17	153263.5	14.8
<i>Hairaydaglyle</i>	Watery	184	77.41	174800	13.45
<i>Kalamile</i>	Colorful	155.66	84.52	147877	12.5
<i>Gerwanlayele</i>	Watery	174	109.38	108228	11.83
<i>Hawawisa</i>	Looks ripen	101.33	119.92	96263.5	11.54
<i>Adomuluhta</i>	White and salty	197.33	90.31	122739.3	11.08
<i>Asakurkura</i>	Ball shaped	140	54.06	87080	4.7
<i>Geleweiti</i>	Mixed colors	82.3	60.02	78185	4.69

The base source was compiled from the scientific work of [33] and was validated via field observations in Hawzien, Edaghamus, Raya Azebo and Enderta in 2021

We quantified the temporal wasted opportunity (missed benefits) of the destroyed cactus. Earlier, [17] applied the “Peru Cactus Production Model” to compute the missed opportunity of cochineal yields. Similarly, the annual carmine cochineal yield (Y_c) of the study area that would have been harvested was computed as follows [17]:

$$Y_c = A_i * P_c * H_f \quad (3)$$

Next, we computed the annual income missed based on the carmine yield (Eq. 3), and the present market price (P_m) that would have generated (I_{ac}) was computed using the following equation:

$$I_{ac} = Y_c * P_m \quad (4)$$

Descriptive statistics were carried out to analyze the quantitative data, whereas a narration and content analysis were utilized to analyze qualitative data.

3 Results and discussion

3.1 Characteristics of *cactus* case studies

Based on the global search engines, we found 63 articles related to the benefits, survival threats, and management practices of cacti. Temporally, these articles were published between 1992 and March 2022. Figure. 2 depicts the temporal distribution of cactus studies. After 2010, the number of publications increased over time (Fig. 2) due to an international workshop held in Mekelle [23]. This workshop pooled the available cactus investigations that were carried out in the region and elsewhere.

Spatially, the case studies were carried out in southern Tigray, and eastern Tigray, along the western escarpment. Next, limited studies were from the central zone of Tigray such as the Tenbien lowlands, Bizet and Ahferom districts. Here, the number of publications corresponds to those cactus-rich areas.

The case studies focused on enhancing economic benefits, combating soil degradation, mitigating drought, and combating forest degradation (Fig. 3). Moreover, the studies present the expansion of cochineal insects to the free zones in the eastern zone of Tigray which were safe up to the recent period. However, limited case studies have been published on the management of cochineal, despite a severe infestation rate since 2011. This meta-analysis implies that there has been little research available on the management practices of cactus, despite the rapid expansion of the cochineal infestation to other new areas.

According to the literature evidence, the average elevation of the case studies was 2106.9 ± 307 (n = 36) m a.s.l.; the cactus growing sites are found between 1200 and 3488 m a.s.l. The average annual rainfall of the cactus growing areas was also 489.9 ± 123.9 (n = 16) mm/year, which ranges between 270 and 700 mm/year. In view of this, the plant grows in areas with annual rainfall between 50 mm/year [35] and 1678 mm/year [34]. Moreover, the temperature of

Fig. 2 Temporal distribution of scholarly articles on cactus in Tigray (source, metadata)

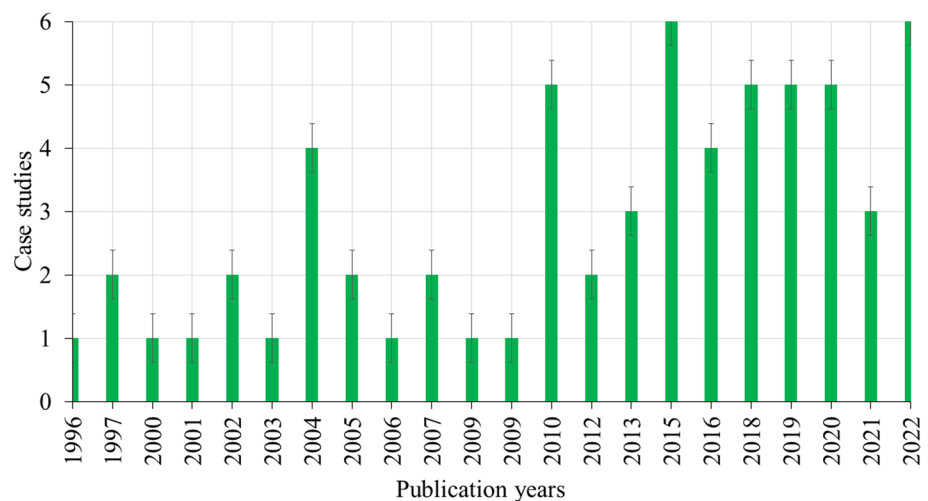
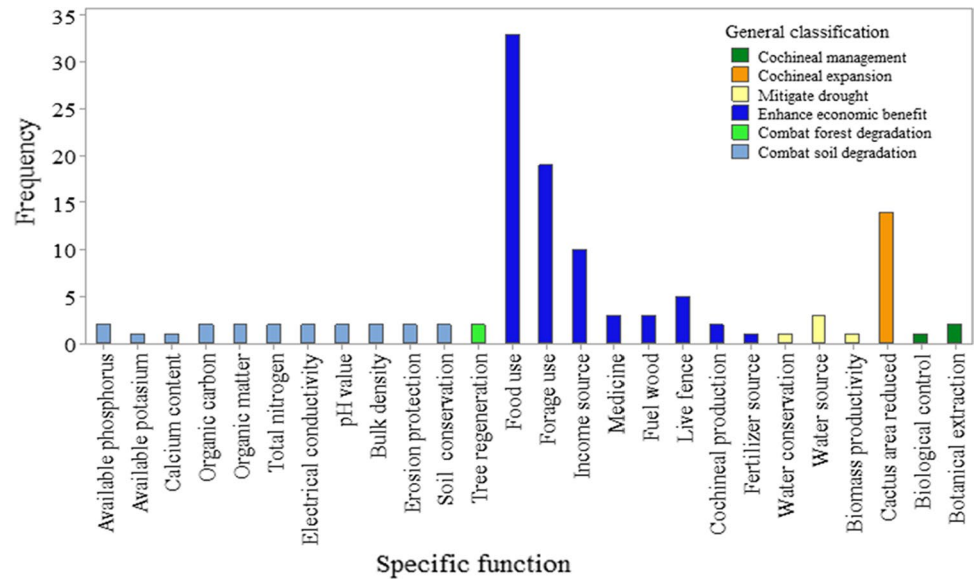


Fig. 3 Frequency of the case studies on the cactus benefits, threats and responses in Tigray



the cactus cultivation area is $23.4 \pm 7.20^{\circ}\text{C}$ ($n = 9$). Fortunately, the cactus plant could tolerate temperatures up to 70°C [35]. In summary, our evidence reveals that cactus plants grow on a wider geographical scale in harsh environment.

3.2 Cactus as a multipurpose dryland plant

3.2.1 Catchment rehabilitation effects of cactus

Cactus plantations have been an excellent measure for the rehabilitation of degraded lands. It grows on steep slopes with shallow and thin soil layers, even on rocks with scattered sediments. The cactus plantation conserves soil nutrients on the degraded hillsides (Table 2). Besides, it serves as a biofertilizer to improve soil properties [35]. In particular, it serves as a material for a ground surface mulching [5].

Phosphorus was higher under the cactus canopy (306 ppm) than in the adjacent open area (40 ppm). In addition, soil organic matter increased from 3.31% in the non-cactus area to 6.63% in cactus-rich areas (Table 2). The plant has increased total nitrogen and soil available phosphorus. Moreover, a higher nutrient content under cactus cultivation was associated with the decomposition of organic materials (Table 2).

Table 2 Comparison of soil properties sampled at 0–20 cm depths between cactus and non-cactus plots (with an average 63 representative plots) in Erob and Raya Azebo (Fig. 1)

Ecosystem function	Cactus canopy	Adjacent open area
Available phosphorus (ppm)	306	40
vailable potassium (meq/100gm)	0.13	0.11
Calcium (meq/liter)	7.92	7.66
Total nitrogen (%)	0.25	0.20
Organic carbon (%)	2.48	1.82
Organic matter (%)	6.63	3.31
Electrical conductivity (ds/m)	3.29	3.13
pH value	4.52	4.20
Soil moisture (%)	9.49	6.74
Bulk density (g/cm ³)	1.17	1.38

Source: [37–39]

Cactus plantations could generate a carbon sequestration of 20 tons of dry matter (equivalent to 30 tons of CO₂) per ha per year [12]. The cultivation of the plant increases soil microbial biomass and activity. Interestingly, this storage of carbon in the soil, in turn, mitigates climate change.

As a biological barrier to soil erosion, cactus cultivation improves soil structure and soil porosity (Table 2). The highest soil bulk density (1.38 g/cm³) was observed in the cactus-cleared area, whereas the lowest was observed in the cactus plantation (1.17 g/cm³). Moreover, the soil moisture content increased under cactus canopy cover (9.49%) compared with open areas (6.74%). Furthermore, the total soil losses in the cactus area (1.98 tons/ha/year) were lower than those in areas without cactus cover (29.1 tons/ha/year) [6].

As a supporting ecosystem service, cactus benefits local biodiversity. In this context, [5] noted that cactus provides wildlife with food, pollen, habitat, and shelter. In addition, above-ground biomass productivity increased in the cactus growing area. Moreover, cactus-covered areas are less exposed to animal grazing and other purposes. In fragile environments, cactus restores the vegetative cover of degraded landscapes [40]. Overall, cactus is an important biological measure for the restoration of degraded catchments. In line with this, the plant is used for erosion control, land reclamation, rehabilitation, and agricultural development [38, 41–44].

3.2.2 Cactus mitigates drought

Cactus has a unique morphological adaptation mechanism for drought. Our qualitative analysis shows that cactus has good tolerance to drought and surface heat. According to the local narrative, cactus is called the “camel of the plant world” in the drylands [45]. As it stores a lot of water during the few rainfall events, the species survives up to 90% loss of its hydrated water content. It has what is called “rain roots”, which develop within a few days after a rain shower event. Moreover, cactus roots collect a sufficient water budget [46]. Hence, [47] found that cactus has an amazing water storage capacity in the drylands.

Cactus is a drought-tolerant species that can be used as an alternative to cereals in semiarid ecosystems. Hence, the plant provides higher aboveground biomass than conventional crops grown in semiarid and arid regions [48]. In particular, the presence of a few stomas per unit of surface area of cactus helps to reduce plant transpiration during the day [49].

Cactus uses a drop of water very efficiently during the dry period. It produces a high amount of dry matter per unit of water consumed [50]. The biomass generation of the plant per unit of water was greater than that of grasses (C₃) and broadleaf (C₄) species (Table 3). Cactus also has a higher water use efficiency (water use efficiency is the ratio of the CO₂ fixed in photosynthesis to the water lost through transpiration) than the C₄ plants (Table 3). Hence, it is reported that cactus is a better water saver than wheat and maize stable crops (Table 3).

Cactus has the lowest amount of water lost via transpiration (the transpiration ratio is the amount of water lost through transpiration over the CO₂ fixed in photosynthesis) in the photosynthesis compared with C₄ plants [3, 6, 50].

Water intake in livestock decreases with the progressive feeding of cactus cladodes. According to the metadata [e.g., 50], the water content of cladodes is nearly 88%. According to [51], cactus provides 180 tons ha⁻¹ year⁻¹ of good quality water for livestock, which is crucial during drought times. Other studies found that cactus mitigates water shortages in the drought-prone dry areas of the tropics [4, 52]. Therefore, cactus is a natural reservoir of water in the face of rainfall and temperature variability. Therefore, the impacts of climate variability and change are minimized and neutralized through massive cactus cultivation [2].

3.2.3 Livelihood benefits of cactus

Cactus has been part of agricultural systems in arid and semiarid regions. The cactus fruits are the main source of food for humans. Based on its merit, rural farmers have given various names to the cactus fruits (Table 4). In cacti growing areas, it is perceived that a “farmer without cactus is like a stream without water”. Cactus fruits are the bread of the poor farmers (Table 4).

It is perceived that “cactus is food from the heavenly God”. Cactus is a lifeline for farmers during drought periods. According to [8], cactus is a “bridge of life”, as it provides food for herders. In other areas, the plant is the secret of a

Table 3 Water use efficiency and transpiration rate of cactus, wheat and maize [7]

Variable	Cactus	Wheat (C ₃ plant)	Maize (C ₄ plant)
Water use efficiency	0.013–0.040	0.0013–0.005	0.0025–0.010
Transpiration ratio	25–80	200–800	100–400

Table 4 Local sayings/songs in relation to the benefits of cactus

Local saying/songs linked to the of cactus merits	Source
A farmer without cactus is like a stream without water	This metadata
Cactus is a food from the heavenly God	This metadata
Cactus is bread of the poor people during conflict	This metadata
Shepherds do not need to turn back to their home for lunch	This metadata
Cactus is bridge of life	[8]
Cactus is hearty weed	This metadata
Cactus is green gold	This metadata
Cactus is American's red gold	[53]
Cactus is gift of the new world	[15]
Oh my beles you spare me this summer till barley has cheerfully come to rescue me	[54]
Cactus is a symbol of hope wishing to return to their expropriated lands	[5]
Cactus is a magical fruit	[55]

magical fruit [55]. Moreover, [56] added that cactus is the 'green gold' of Jordan. For displaced people, the cactus tree is also a symbol of hope, wishing to return to their expropriated lands [5].

Edible parts of cactus are young cladodes and fruits. [22] suggested that young cladodes are an excellent source of proteins and vitamins for humans; they have high nutritional value. It was also reported that fruits provide food nutrition [57]. Moreover, [58] pinpointed that the nutritional value of cactus fruits is equivalent to that of apple and orange. Importantly, fruits reduce the total cholesterol content in the human body [59]. It also lowers the body weight and blood glucose levels of diabetic human patients. In general, the crop plant provides an alternative source of food and feed resources in the drylands [51, 60].

Although the fruit yield per cladode depends on its physical attributes, the average number of fruits per plant is 212.4 ± 97.8 (Table 5). In addition, the average fruit weight of cactus is 103.98 ± 30.43 g. With this, the average production of fruits is 16.20 ± 8.33 tons per ha per hear. Based on our computation, the average income of one ha of cactus plantations per year is $\$11,272 \pm 3978$ (Table 5). Hence, greater awareness increases fruit growth and ripening performance [61].

Cactus is an alternative source of forage for domestic animals during scarcity periods. The cactus pads are harvested, chopped into small pieces, and given to domesticated animals (cattle, sheep, goats and camels) as an energy supplement [21]. According to [52] and our lived-field experience, fresh cactus cladodes, which are rich in energy, were excellent fodder sources for 9–12 months of the year. [52] also reported that cactus substitute pasture hay to a level of 60% for sheep production.

Indeed, it supplements low-quality fodder such as wheat straw and alfalfa hay [62]. In line with these findings, feeding chopped cladodes also fulfills the daily water requirements of livestock [63]. Therefore, cactus pads provide a sufficient animal diet at a low cost and become an alternative fodder for sustainable livestock production [64].

During our field visits, we observed that cactus acts as a live fence, defensive hedge, and windbreaking (Fig. 4). The live fence of cacti is a sustainable agricultural practice. The plants are used as biological barriers for livestock (Fig. 4). In agreement with [5], we found that the species is used to delineate the boundary between two adjacent agricultural and dwelling plots. Overall, cactus fruits are used as a coping strategy during food and feed gaps due to conflicts and droughts in the western escarpment. On a larger scale, keeping cactus at homesteads and mountain areas plays a crucial role in meeting the objectives of the green economy agenda in Ethiopia.

Table 5 Optimal economic benefits of cactus cultivars computed based on Table 1

Variable	Mean/total	Standard deviation	Minimum	Maximum
Fruits # per plant	212.4	97.8	82.3	423.0
Fruit weight (g)	103.98	30.43	54.06	146.59
Average # of plants in ha	748.2	166.1	622.0	950.0
Total # fruits in ha	149359	52704	78185	263106
Fruit production (tons per ha)	16.20	8.33	4.69	30.15
Income per ha (\$)	8454	2983	4426	14893

Fig. 4 View of cactus benefits: Cactus (cladodes and fruits) for food and live barrier to protect backyards from live-stock and soil erosion



3.2.4 Perceived local problems associated with *cactus*

Arguably, some farmers labeled “cactus is a fruit of the rural poor”. Consumers showed higher demand for cactus fruit during food gaps. In other words, the importance of fruits increases with the times of famine and drought in the study area. For some, hence, eating cactus products is associated with hunger seasons. Similarly, consumers in South Africa perceived those indigenous and traditional food crops were being labeled “poor people’s food” [65].

Qualitative metadata demonstrates that cactus plantations harbor crop pests, invade croplands and restrict the mobility of people and livestock (Table 6). In addition, bloating and diarrhea were major reported constraints during the feeding of the cactus pads. An earlier study also showed that spiny cactus caused animal tooth loss, death and mechanical injury in livestock [66].

It is perceived that cacti had a negative effect on other vegetation cover. It also suppresses the growth of cash crops (e.g., chat) and field crops. In addition, cactus inhibits the growth of grasses and displaces other vegetation by taking up space. The invasion of cactus species into extensive lands has modified the vegetation composition [5]. Therefore, cacti adversely affect local ecosystems by suppressing forage production and limiting the access of livestock to pastures (Table 6).

In Raya graben (2013–2017), we observed that indigenous biodiversity along the foot of the mountains or graben bottoms was at risk due to aggressive cactus invasions before cochineal infestations. Similarly, it further affects stable crops if cactus is planted near an average distance of two meters [66]. Uses of cactus into farms as hedges encroached on fertile farmlands, and thus the farmers spent a lot of energy to remove the cactus bushes. In addition, cacti harbored wild animals that destroyed crops [39]. Similarly, [67, 69] reported that cactus invasion is a threat to food security in some areas. These perceptions could lead to poor management of the plant in the drylands [15]. In relation to the ecological services (use value) of the plant, however, it should be underlined that perceptions on the disadvantage of cactus is very insignificant.

Table 6 Households’ response to the problem associated with cactus [39]

Uses of cactus problems	Respondents (n = 110 households)	
	Frequency	Percentage
Harbor crop pest and wild animals	102	92.72
Invalidate crop land	85	77.27
Induce diarrhea in animals	37	33.36
Hinder activities by restricting mobility	26	23.63
Physical injury	16	14.54

3.3 Cactus status after cochineal introduction

3.3.1 Cochineal insect management efforts

Cochineal insects were kept for the production of dye in a partly conditioned greenhouse in the Raya Azebo [24]. With permission from the Federal Ministry of Agriculture and Rural Development (ref. no. 21/126/1.1 dated 4/01/97), the insect was released at Tsehafti area of Wejerat, Embachra area in Mehoni and Endayesus compus of Mekelle University on the 12th of September 2004 [17]. Later, however, the insects escaped and dispersed widely from the investment areas to the cactus-rich areas due to the scarcity of management [24]. Despite its impact on the livelihoods of the people, absence of responsibility has worsened the rate of infestation. Thus, the insect has become a threat to local residents and the environment since 2009.

There have been attempts to control the cochineal expansion (Table 7, read the list of country). Based on the meta-analysis, the first response of the regional government was to revoke the license of the investor in 2010 to limit the expansion of the insect to other areas. In addition, practical trainings on the identification of buffer zones between the infested and free areas, strengths of past efforts, awareness creation to farmers and experts, scouting, cutting cactus cladodes with a sign of infection, and burning and burying infested cactus were given to the local people.

Communities were mobilized for mechanical control campaigns. For example, exposing infested cacti to the sun was an excellent move in controlling cochineal (Table 7). Similarly, [68] observed the importance of productive pruning that controls the canopy of the plant and renewal pruning, which involves the removal of earlier orchards and replanting. With the combined efforts, however, it was possible to clear only 9.3% of the invaded cactus area.

Insecticide spray programs were implemented in the more infested sites to halt the rapid rate of infestation (Table 7). However, the presence of rugged terrain, dense and irregular plantations, incised rivers, and floods challenged the spraying of cactus plants with insecticides. Another challenge was that the insecticide damaged beehives and livestock in the area. Moreover, it was reported that the insects were not harvested on time for commercial use due to local resistance and conflicts of interest.

With the help of local wind, the cochineal insects have rapidly diffused into other free areas. It is imperative to know that in the end-northern of the western escarpment in Tigray such as Saesie Tsaedaemba, Ganta Afeshum, Gulomekada, Irob and Ahferom, there were cochineal free districts due to the creation of a buffer zone and the direction of

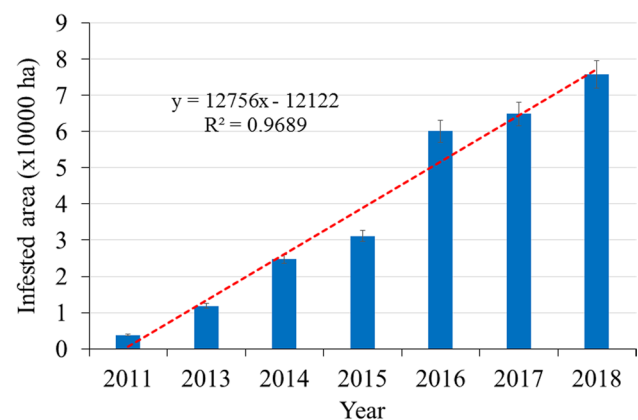
Table 7 Tested lists of better management of cochineal insects which could be important for interventions to save cactus in Tigray

Cochineal management		Country applied	Source
Biological measures	<i>C. montrouzieri</i>	Israel	[74]
	<i>Eosalingogaster</i> Hull	US	[75]
	<i>L. coccidivora</i>	Mexico	[76]
	<i>Leucopina bellula</i>	Mexico	[77]
	Mealybug destroyer	Morocco	[78]
	<i>Hyperaspis trifurcata</i>	Mexico	[79]
	<i>Sympherobius barberi</i>	Mexico	[77]
	<i>Nicotiana glauca</i>	Ethiopia	[70]
Chemical measures	Sulfoxaflor	Lebanon	[80]
	Diflubenzuron	Lebanon	[80]
	Herbal chemical	Ethiopia	[81]
	Closer 240 SC	Ethiopia	[81]
	Rock salt + Detergent	Ethiopia	[81]
	Potassium salt	Spain	[82]
Mechanical measures	Washing + brushing	Israel	[77]
	Burning + cutting + burying	Ethiopia	[81]
Cultural practices	Resistant variety	Dryland countries	[83]
	Spacing + row planting	Italy	[15]
	Pruning (productive + renewal)	Italy	[68]

Fig. 5 View of cochineal cactus infestation due to poor management (A-B) in Tigray



Fig. 6 Temporal variation in the cochineal infested area in Tigray (source, metadata)



winds. With the absence of management during locust invasion, Covid-19, and Tigray War (2020–2022), we found that the pest rapidly increased to nearby cactus-rich new areas towards the eastern zone of Tigray.

Based on our ground-based experience, the Tigray Bureau of Agriculture and Rural Development, Ministry of Agriculture, Tigray Agricultural Research Institute, Tigray Institute of Policy, higher research institutions such as Mekelle University, Axum University, Adigrat University, and Raya University and other federal institutions and stakeholders have failed to address the adverse impacts of cochineal pests. Consequently, the multifunctional cactus has been under threat [Fig. 5, 69].

3.3.2 Cactus has been under threat

As indicated in Sect. 3.3.1, the multipurpose cactus plant was destroyed by cochineal insect (Fig. 5). The cochineal insect became a threat to the local residents and the total environment [70].

On average, 3890 ha of cactus area per year was destroyed in the area. The annual rate of cochineal infestation (presence) between 2011 and 2018 was 31% (Fig. 6). Spatially, the infested areas increased from 17 villages in 2011 to 139 villages in 2018. Our observation reveals that the infestation area progressively increased after 2018. According to the metadata, more than 50% of the total cactus area (16,255 ha) was infested in the study areas. It should be noted that the damage of the cactus area varies in space, and much of the cactus area in southern Tigray was heavily damaged by the pest. Recently, [69] also reported that the insect damaged about 15,489 ha in Raya-Azebo as well as 3,165.5 ha in Enda Mehoni district of southern Tigray.

Climate variability affects the rate of cochineal pest production [71]. For example, rising temperature drives a cochineal invasion in the study area. An area having an annual average temperature of 22 °C is a suitable condition for multiplication of the insect [8], where the study area is in this temperature range. In view of this, climate change will exacerbate

the cochineal insect which will help to spread to the new areas [72] as less hotter areas ($< 22^{\circ}\text{C}$) will get hotter in the near future.

Farmland expansion toward hillsides was another factor which reduced cactus distribution in the study area. Our frequent observations (between 2013 and 2017) in the Raya graben indicated that new agricultural investment (irrigation business) in the fertile plains decreased cactus cover as they cleared cactus for other cash crops. In the graben system, [73] also reported that agricultural investors removed massive cactus plants. We observed that an increasing camel population from the Afar lowlands induced rapid destruction of cactus cover. Furthermore, farmers with a relatively large number of animal holdings were forced to destock homestead cactus.

3.3.3 Missed opportunities from *cactus*

The cochineal insects were not harvested on time for commercial use. The carmine cochineal insect harvest would have increased from 3,025 tons in 2011 to 60,253 tons of dye in 2018 (Fig. 7). Out of this pool of dye harvests, 24,012,200 dollars would have been obtained from the carminic acid. The qualitative meta-analysis also showed that the expansion of the pest was a source of conflict. Moreover, [24] reported that the “fortune” for carmine cochineal yield was missed due to an uncontrolled pest infestation.

The rural communities did not receive income from commercial insects or cactus fruit sales and other biomass from their homesteads, agroforestry and mountains as what was before the introduction of the insect. Indeed, we observed that the wider and rapid pest infestation damaged the provisioning services of the plant, such as food and feed and medicines. To conclude, the poor farmers received neither the benefits of the carmine cochineal yields nor the benefits of ecosystem services. The opportunities for cactus for the farmers were lost due to lack of insect management.

3.4 Proper *cactus* management for a better ecosystem service in the drylands

3.4.1 Global experience of cochineal management

The scarcity of cochineal management (Sect. 3.3.1) led to a total eradication of cactus (e.g., Sect. 3.3.2), and thereby farmers missed the benefits of cactus (Sect. 3.3.3). Thus, agricultural experts, scientists and other stakeholders need to respond to the expansion of insects and secure cactus survival in the study area (Table 7).

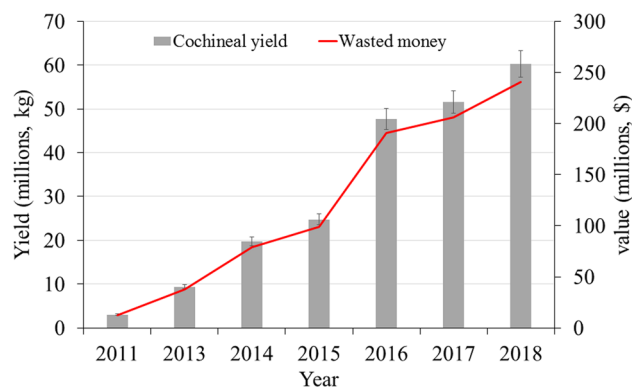
Table 7 presents biological, chemical, mechanical and cultural practices known as good global cochineal management. Notably, the biological control is an efficient management strategy to reduce the problem of the pest in a sustainable way.

For example, the use of a mealybug destroyer has reduced the cochineal (*Dactylopius oontie*) population up to 92% in Morocco [78]. *Laetilia coccidivora* and *Eosalphingogaster cochinelivora* in Mexico, caused almost 100% destruction of cochineal farms in greenhouses, and approximately 50% damage to cochineal farms in San Luis Potosi [81].

Laetilia coccidivora has been used as biological control measure for the insect. In Israel, high activity of natural enemies and the decline of cochineal populations were noticeable in 2017 [78]. A very recent investigation also indicated that there are potential resistant cactus cultivars, and these varieties are crucial integrated pest management strategies for the environment and for producers [83].

To conclude, integrated pest management practices, including biological, chemical and mechanical measures, will lead to sustainable cactus production and to mitigate invasive pests in the study area and beyond [84]. To this effect, we

Fig. 7 Trend of cochineal yield (in kg) and corresponding missed income (million in \$) that would have generated in the study area (source, metadata)



call upon the international community to conduct action research to protect the valuable plant and maintain ecosystem services.

3.4.2 Cactus cultivation opens new livelihood opportunities for farmers

Integrated pest management practices control cochineal infestations in Tigray. Such management practices optimize cactus uses: food, forage, firewood, a source of income, and other ecosystem services (Figs. 3, 4 and 7, Tables 3, 4 and 5).

A better local awareness of nutritional value of cactus benefits exists in cactus-rich areas of Tigray. The cactus fruit has become the major income and food source. We observed that urban and rural residents have increased cactus fruit consumption, mainly during July, August and September. The attractive market value of the fruits has increased in the villages, towns and cities. As a result, it will motivate smallholder farmers to expand cactus planting at their homesteads and other parcel of plots. In spite of the challenges of cochineal insects, we observed that farmers have been cultivating the plant at homesteads and communal lands in search of alternative livelihood means during shocks.

Investing in cactus cultivation along the Great Western Escarpment in the northern Rift Valley system of Ethiopia could be a new opportunity for rural farmers. In this geographical region area, which is characterized by frequent, intense and longer drought conditions [27], this multipurpose cactus plant will enhance the environmental, social and economic goals in the face of frequent droughts (Fig. 8, Table 4).

Approximately 50% of the landmass of Ethiopia suffers from water shortages as well as the undulating characteristics of the landscape. Therefore, the cactus plant is worth expanding to the degraded hillslopes and drought prone areas along the western Afar margin and semiarid midlands. In particular, increasing cactus belts in the western escarpments break the advancing desertification from the Afar area toward the highlands and to further ensure sustainable uses of cactus.

Sustainable cactus management capitalizes on supporting, regulating, provisioning, regulating and cultural ecosystem services (Fig. 8). In the drylands, including the study area, we need to focus on tolerant cactus species to both natural and

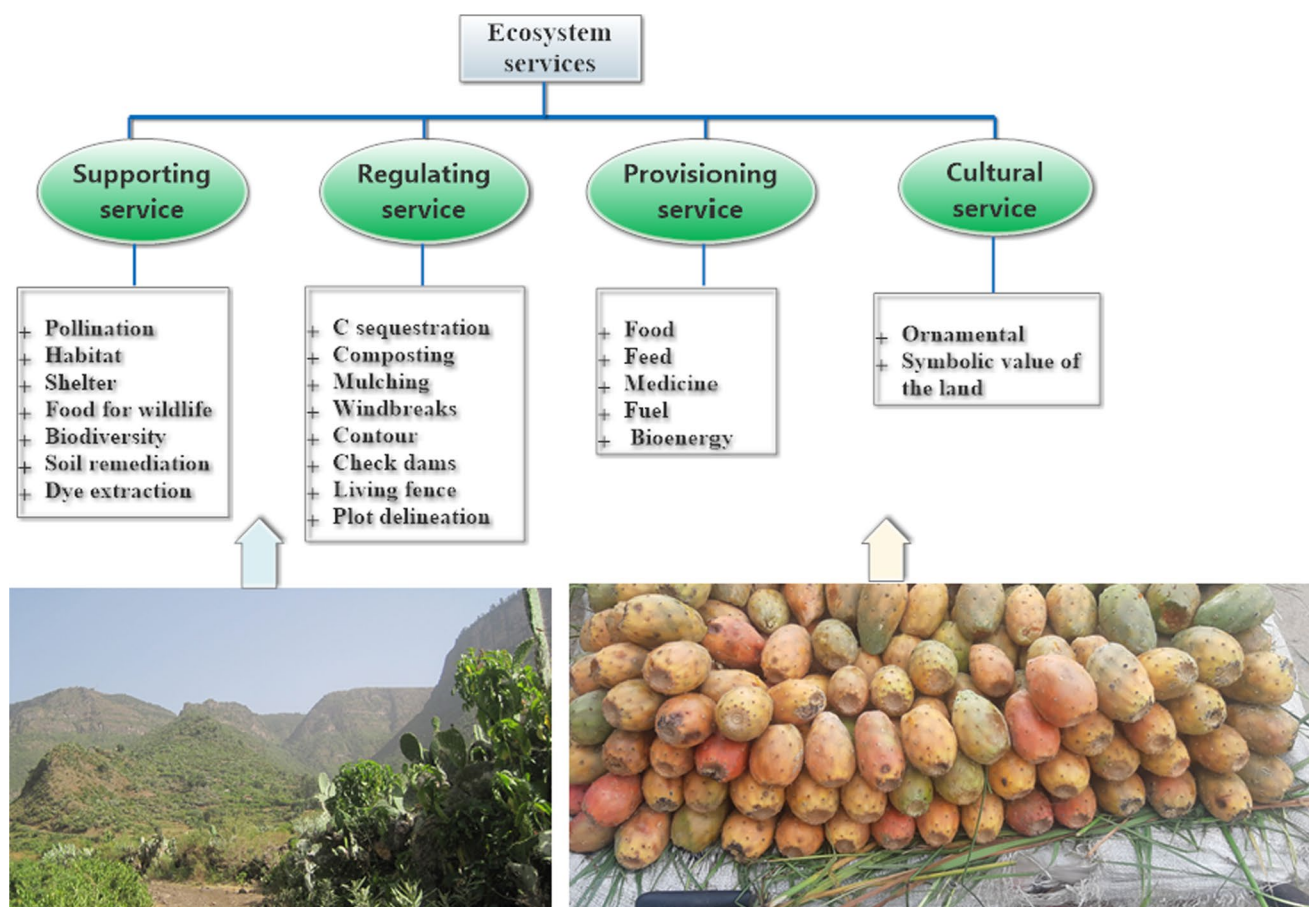


Fig. 8 Proper management of cactus strengthens its linkage with ecosystem services

human factors to improve the livelihoods of farmers and the environment. [85] further underscored that drought-tolerant succulent plants as an alternative crop under future global warming scenarios in sub-Saharan Africa.

4 Conclusions

The objective of this study was to synthesize the literature evidence of ecosystem benefits, survival threats, and management of cacti along the western escarpment of the Rift Valley. The meta-analysis shows that cactus plant controls soil erosion, regulates climate variability, and conserves habitat. In terms of its provisioning services, fresh cactus fruits and young cladodes are readily available as fast food for consumers, mainly during natural and man-made shocks. The cactus cladodes at homesteads are also feed sources for livestock during the critical period in the drylands. Cochineal insects were introduced to add economic value for the poor farmers and the environment. However, the insect heavily destroyed cactus plant due to poor management and the failure of research institutions to address it on time. As a result, Tigray has been rapidly missing the multifunctional crop plant over time. The meta-analysis highlights that researchers, regional government and other stakeholders have failed to control the pest for more than a decade. Therefore, these actors who were active during the introduction of the insect must combine their efforts to restrict cactus infestation. With the help of research institutions and farmers, cactus plants should be cultivated at homesteads, degraded lands, hilly sites, edge of croplands, and communal areas to improve farmers' livelihoods and ecosystem functions during natural and anthropogenic shocks.

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Author's contributions Hailemariam Meaza: Conceptualization, methodology, formal analysis, original draft, supervision, review, and editing; Biadgilgn Demissie: Preparation of the map, review and editing; Yemane Kahsay Berhe: Supervision, review and editing. Misgna Gebrehiwot: review, and editing; Jan Nyssen: Supervision, review, and editing; Mitiku Haile: Supervision, and review; Amleset Gebreegzabher: Review, and editing, and Abbadi Girmay: Supervision, review, and editing. Next, all authors read and approved the final manuscript.

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Data availability No data available. All data are used in this article.

Declarations

Ethics approval and consent to participate The subject of this study is not linked to the ethics for consent declaration. All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests We declare that the authors have no competing interests.

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