# Taro in West Africa: Status, Challenges and Opportunities

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**Abstract:** Taro is an ancient nutritional and medicinal crop that has been woven into the fabrics of the socio-economic life of people in the tropics and sub-tropics. However, West Africa (WA), which is the major producer of the crop for several decades is experiencing significant declines in production due to the occurrence of taro leaf blight (TLB) disease caused by *Phytophthora colocasiae* Raciborski. Research work on taro in WA is scanty and has not leveraged available innovative technologies to proffer the solutions to inherent challenges and enhance the status of the crop. Improvement through plant breeding remains the most economically and environmentally sustainable means of increasing the production and productivity of taro in WA. In this review, we have tried to provide an insight into the importance of the taro crop in WA, evaluate the position of taro research, and suggest ways of filling such gaps for its sustainability in the region.

insights

research in order to promote sustainble

**Keywords:** Taro; Taro leaf blight; *Phytophthora colocasiae*; taro improvement; West Africa

## 1. Introduction

Taro [*Colocasia esculenta* (L.) Schott], a member of the family Araceae and sub-family Aroideae, is a tropical monocotyledonous vegetatively propagated perennial crop grown primarily for its starchy corm or underground stem. It is one of the world's oldest food crops, dating back over 9,000 years. Taro was first domesticated in Southeast Asia, and thereafter continued to spread across the world and is now one of the most important staple food crops in the Pacific Islands and is widely distributed in Africa, Oceania, Asia and the Americas [1-2]. Taro is the most commonly cultivated species in the genus *Colocasia* [3], and is the fourth most consumed tuber crop globally [4]. This crop has been largely maintained by smallholder farmers and taro genetic resources have remained largely with the local communities [5]. In many cultures, taro is considered as a sacred plant with strong cultural importance, and used in religious festivals, domestic or agricutltural rituals, and as a bride price [5, 6].

3, 4 seem weak secondary sources wrt to global

Taro is an important food crop for millions of people in many parts of the Africa, widely grown as a backyard and intercrop [6-10]. It is also used as an ornamental plant [11]. It is a staple food for millions of people in West Africa (WA) and can therefore be found in virtually all countries in the region [12]. Taro contains about 35 g of total carbohydrate per 100 g of corm, and this is twice as that in potatoes [13]. It also contains 11% protein on a dry weight basis and rich in minerals, vitamin C, thiamine, riboflavin and niacin [14]. Taro is nutritionally better than many cereals such as rice, wheat and sorghum in terms of Vitamins C, E and potassium [13]. Besides its nutritional value, taro is often used as a traditional medicinal plant providing bioactive compounds with important properties [15]. In 2020, more than 12.8 million tonnes of taro was produced worldwide from 1.8 million hectares [16]. According to FAO production data for 2022, Nigeria is the largest producer of Taro with a global share of 25% followed by Ethiopia, China, Cameroon, Ghana and Papua New Guinea [16]. In WA, taro is reported to be produced in all the countries except Guinea Bissau, Guinea, Sao Tome and Principe and Cape Verde

Reported by who? Cite 9,12,17 after "countries"

where there is a paucity of information on its production [9, 12, 17]. Taro production in WA is bedeviled by the emergence of taro leaf blight (TLB) caused by *Phytophthora colocasiae* Raciborski [18, 19, 20, 21]. Since its outbreak in WA, TLB accounted for an economic loss of more than $1.4 billion annually leading to the genetic erosion of this crop in the region [18].

This article presents a review on the origin, domestication, and dispersal of taro, and evaluates the extent of research on its improvement in West Africa, to identify the gaps and provide recommendations towards a revival of its production, to meet the nutritional demands and contribute to food and income security of smallholder farmers.

## 2. Origin, Domestication, and Dispersal of Taro

It is estimated that taro originated in the tropics ranging from India to Indonesia [22]. This is further supported by Chair *et al.* [8] who reported the presence of higher genetic diversity among the genotypes collected from Asia compared to those from the Pacific, Africa and the Americas. It is believed that taro is among the oldest cultivated crops and was used 28,000 years ago in Solomon Islands [23]. With high genetic diversity reported among Indian germplasm, it may be concluded that taro was domesticated in India and then spread to the countries in Asia-Pacific region [8]. It is also believed that a secondary domestication of taro must have happened in New Guinea [24]. Lebot also reported that all cultivars in the Pacific are diploids, produce flowers, and get naturally hybridized through insect pollination contributing to high genetic diversity or clonal richness.

Taro was presumed to have reached West Africa through human ~~migration~~ and most cultivars are probably of Indian origin [8]. It is also likely that taro was introduced to Africa together with bananas and greater yam (*Dioscorea alata* L.) [25]. Clonal propagation combined with natural mutations probably is the reason for taro diversification in Africa. Taro is also found in the wild and the greatest diversity of wild *Colocasia* species appears to extend from northeast India to Southern China. As a food, medicinal, ornamental or fodder plant, the geographical range of wildtype taro has been extended by humans, with or without cultivation. The place of first use and natural range of wildtype taro is unknown, and complicated by the possible reversion of domesticated forms to wildtype in some areas [22].

## 3. Genetic Diversity of Germplasm Resources for Improvement

Taro belongs to the family Araceae which is a large, ancient, monocot plant family characterized by ~~its~~ morphological diversity [26]. It was suspected to have originated from the Indo-Malayan region based on the enormous varietal diversity [27]. The number of species in the genus *Colocasia* ranges from 5 to 10, with taro (*C. esculenta*) as the most widely cultivated species with over 10,000 landraces worldwide [28]. Taro is highly polymorphic and two cultivar types widely cultivated are: *C. esculenta* var. *esculenta*, called the 'dasheen' type which has a large cylindrical corm with few or no cormels; and *C. esculenta* var. *antiquorium*, called the 'eddoe' type which usually has a small globular corm with several cormels [29]. Most taro cultivated in Asia and the Pacific are the dasheen type. Typically, *C. esculenta* are propagated by asexual reproduction but it can also reproduce sexually through its protogynous flowers with the aid of insect pollinators or mechanical means [27, 30]. It has high plasticity in adaptation and thus can be found in varying environments ranging from full sunlight to deeply shaded regions, and from dry soils to saline and flooded soils [31]. Taro is a crop with a hyper-diversity, this is the probable reason for its resilience in adaptation to variable environmental conditions [32, 33]. The genetic base of taro as an introduced crop in Africa and the Americas is usually narrow [8, 32, 34]. However, this can be broadened through introduction of new germplasm and widen the crop's ability to withstand the possible vagaries of climate variability and associated biotic and abiotic stresses [32]. It is therefore necessary to understand and assess the extent of genetic diversity of taro within a region to identify gaps that will aid in planning missions for additional germplasm collection or introduction of new germplasm [5].

22 is out of date source and not primarily, on topic cf Ahmed, I., P. J. Lockhart, E. M. G. Agoo, K. W. Naing, D. V. Nguyen, D. K. Medhi and P. J. Matthews (2020). "Evolutionary origins of taro (Colocasia esculenta) in Southeast Asia." Ecology and Evolution 10: 13530–13543.

"Lebot" is not proper citation; cite Ivancic, A. and V. Lebot (2000). The genetics and breeding of taro. Monpellier, CIRAD. for description of insect pollination and natural outcrossing by taro. "Hybridisation" refers to crossing between very ditinct parents or species; not all breeding produces

introduction, not "migration"

22 may have written these sentences, but other papers by same author are better sources; avoid direct copy and paste of text, or use quotation marks

by high morph...

Several studies that documented the genetic diversity of taro from Asia and Oceania revealed greater variation in Asia. A global experiment including taro cultivars and improved hybrids across 14 different countries of Asia, Africa, America and the Pacific showed that the introduced genotypes get readily adopted by the farmers as their needs get satisfied [32]. In this study, 50 introduced genotypes were compared with local cultivars in a participatory method to strengthen smallholder farmers capacity to adapt to climate changes, and also to broaden the genetic base of the crop to cope with climate variability. The majority of taro cultivars found in West Africa are believed to have originated in India. Indian cultivars are reported to be cytogenetically variable, with variable chromosome number and ploidy levels (diploids and triploids) [8]. Several studies on genetic diversity in taro grouped majority of cultivars as diploids with 2n = 2x = 28 chromosomes, triploids with 2n = 3x = 42 chromosomes while tetraploids (2n = 4x = 56) are rare [8]. There are also reports of cultivars with a basic chromosome number of n = x = 12 [34]. This difference in ploidy levels among cultivars (diploids and triploids) impedes hybridization and gene flow among cultivars, thus reducing the extent of genetic diversity in WA [8].

**4. Taro Production in Africa**

The current distribution of taro as a cultivated food crop extends from southern to northern Africa [6, 35], western Asia to eastern Asia, across Southeast Asia and the Pacific Islands, and through the Americas, from the USA to Brazil [36]. The root crops that play an important role in many African countries are potato, cassava, sweet potato, yam, taro and cocoyam [37]. There are numerous taro cultivars found across West Africa and occupies an important role in local agriculture and traditions indicating a long history of this crop in this region. Figure 1 represents the countries where taro is being cultivated in Africa between 1961 and 2020, indicating that taro is currently cultivated in hot, humid areas with high rainfall such as tropical sub-Saharan region, but can also be found in drier regions along streams such as Egypt, Algeria and Libya. However in Africa, changes in environment and agricultural systems have led to a decline in taro production. Within Africa, four countries such as Nigeria, Ethiopia, Ghana and Cameroon accounted for about 67% of total production in 2020 [16]. Despite its wide geographical presence, there is limited research efforts and funding for large-scale assessment of production, trade and usage of this crop. In addition, taro thrives under diverse agroecological and soil conditions and referred to as an ecological friendly crop [38]. It produce optimally in altitudes extending from 60-1850 m above sea level in the tropics and temperate zones [7, 39, 40].

Traditionally, taro is propagated using corms, cormels, suckers and tops (huli). The use of tops and suckers are preferred because the duration of growth from planting to harvest is shortened when compared to the use of cormels, corms or corm pieces (setts), though cultivars with many suckers produce smaller corms [38]. The yield of taro is optimized when the soil is appropriately managed and agronomic practices properly carried out [5]. On average, taro requires a well-drained sandy loam soil with good water retention capacity, and it does well with application of NPK fertilizers [30, 41]. Quality organic materials and bio-fertilizers (Mycorrhizae, Azotobacter and Phosphorine) can also be used, by furrow placement and split application, respectively [5].

it is better to use "new cocoyam" for Xanthosoma spp. in Africa

Fig. 1 is OK but Grimaldi, I. M. (2016) can be cited for more complete map of distribution in Africa:

(2016). Taro across the oceans, journeys of one of our oldest crops. News from the Past, Progress in African Archaeobotany. Proceedings of the 7th International Workshop on African Archaeobotany in Vienna, 2 – 5 July 2012. U. Thanheiser. Groningen, Barkhuis: 67-81.

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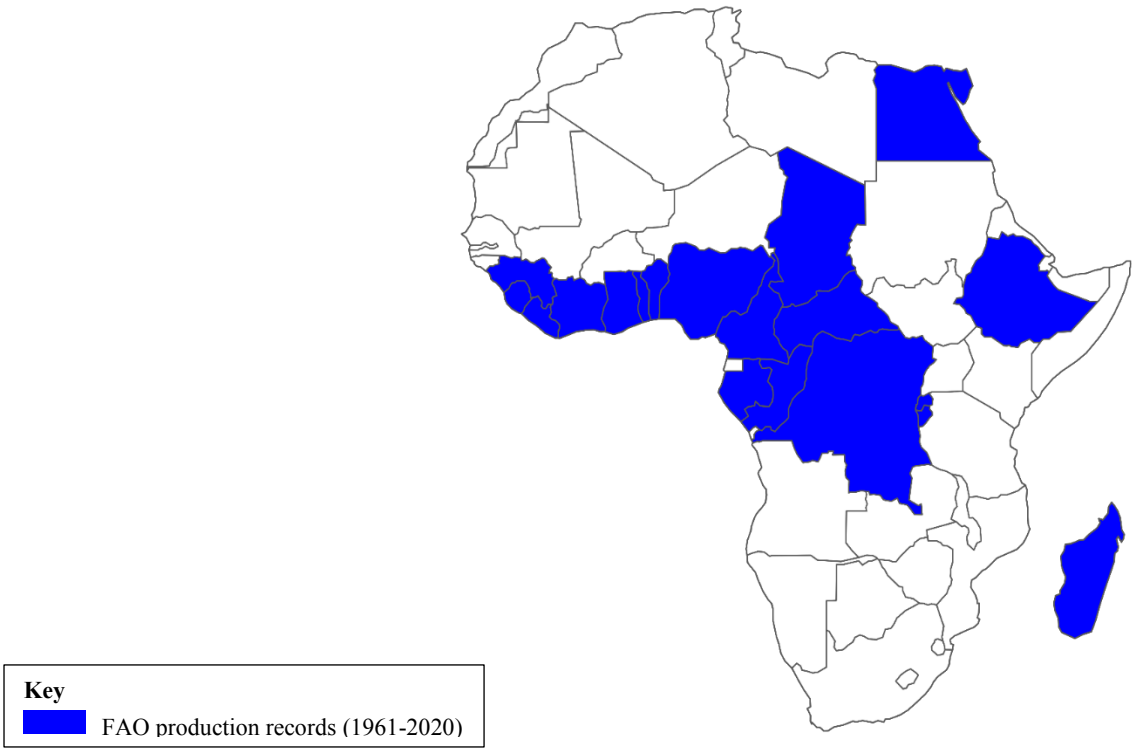



**Figure 1.** Map of taro production in Africa based on FAOSTAT data from 1961 to 2020.

## 5. Taro Production Trends

Data on taro production and consumption is limited. The Food and Agricultural Organization Crop Production Statistics (FAOSTAT) includes data for 47 major taro-producing countries globally [16]. However, production data in several countries where more taro is consumed as a traditional food crop is not accounted in FAO global statistics as most production is either under backyards or intercrop [42, 43].

Globally, taro ranks 5th and 17th among root and tubers and among staple crops, respectively with about 12 million tonnes of production from about 2 million hectares with an average yield of 7 t/ha [16]. Globally, taro production in terms of total area harvested increased substantially in the last two decades. Most of the global production comes from developing countries characterized by smallholder production systems relying on minimum resource inputs [44]. Based on FAOSTAT [16], Africa contributed over 70% of taro production worldwide consistently in the past two decades while accounting for about 76% of world share in 2000. However, there was a decline in production levels from 2009 attaining about 77% (9.3 million tonnes) of world production in 2019 (the highest in two decades). This increased production in the African region depended largely on increased farmland for taro production rather than increased crop yield per hectare [18]. The average yield per land area (tons/ha) in Africa has been relatively low (Figure 2), from 6.60 tons/ha in 2000 to 5.80 tons/ha in 2019 while Nigeria, the leading taro producer, experienced a decline from 6.62 tons/ha in 2000 to 3.91 tons/ha in 2019 [16]. African region recorded the lowest taro yield per land area in 2020 when compared with other regions such as Asia (16.3 tons/ha), America (11.0 tons/ha), and Oceania (9.0 tons/ha). This yield difference in Africa could be attributed to limited input use, taro cultivation on marginal lands and the emergence of taro leaf blight (TLB) in West Africa in 2009 [18].

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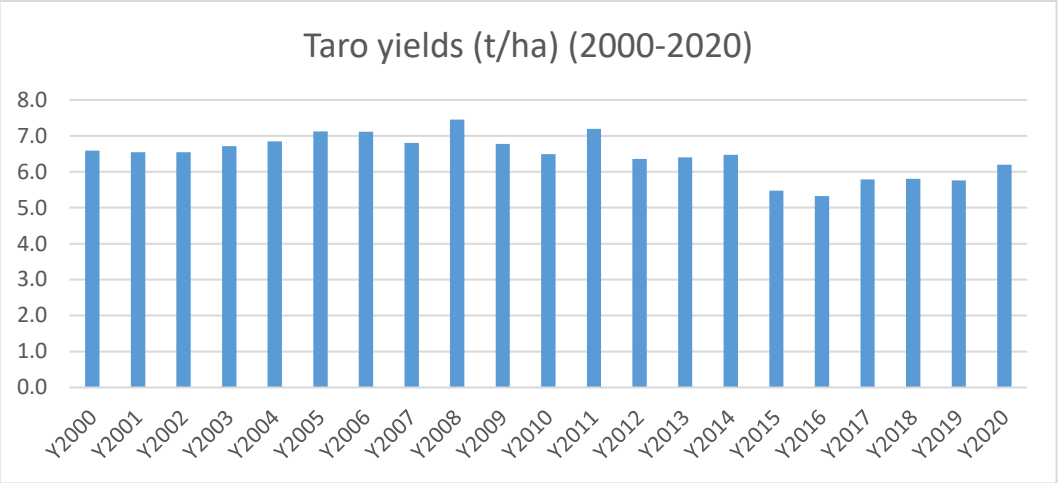



**Figure 2.** Taro yield trend from 2000-2020 in Africa (FAOSTAT, 2022).

## 6. Taro Production Constraints in Africa

The major biotic stress that besets taro is the taro leaf blight (TLB) disease caused by *Phytophthora colocasiae*, a oomycete disease with highly devastating effects [45]. *P. colocasiae* was first reported in Java by Raciborski [46] and ~~presently, it~~ is distributed all over the tropics [48, 49]. The disease thrives in places where the day and night temperatures range from 25-28°C and 20-22°C, respectively, and can assume epidemic proportions all year round under favorable conditions [47]. TLB was not known in WA until 2009 when there ~~was a~~ simultaneous outbreak in Nigeria, Cameroon, Ghana, and other neighboring countries [20, 21]. It is estimated that an economic loss of about USD 1.4 billion annually occurs due to TLB in WA [18].

and is now distributed...

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*Phytophthora colocasiae* reproduces asexually during rainy seasons, with the production of sporangia from sporangiophores at the lesions' extremities in infected leaves. The sporangia leave the pedicel behind during rain and germinate to produce motile zoospores which can swim for short distances in water and encyst to form germ tubes for penetration into the host. This can happen within two hours at a favourable temperature of 20°C and a minimum of 90% humidity. At an ideal temperature of 24-27°C, symptoms show 2-4 days after penetration of the germ tube [48, 49]. *P. colocasiae* is heterothallic with two mating types, A1 and A2, and can produce oospores by sexual reproduction [50].

Zoospores and sporangia are the major means of spread for *P. colocasiae* on the field. The propagules are short-lived in the infected leaves and tissues, and are carried by water to the host through rain splashes [49, 50]. Taro corms are, however, rarely harvested from the field and can sustain the pathogen. The majority of the time, planting is carried out within a short time after harvesting thereby making the infected tissue debris left in the field a source of inoculum for subsequent infection of the new plants [50, 51]. An entire field may become symptomatic ~~of~~ the disease within seven days when the conditions are favorable [18, 47]. The symptomatic plant initially shows water-soaked lesions within a diameter of 1.5 cm around the leaf edges, the fluid exudates from the lesion give a bright yellow to dark purple color when dried. As the disease progresses, the lesion enlarges giving a zonate look characterized by a brownish to purplish-brown color. White fuzzes also appear on both sides of the leaves showing the sporangia, which continues until the leaf is taken over [47, 48]. The white fuzz of sporangia around the lesions is the characteristic symptom of *P. colocasiae* infection [48]. The infected leaf tissues collapse after 20 days, unlike the healthy ones that spend up to 40 days before collapsing [51]. TLB also affects the corms causing them to rot, and yield losses due to this disease could be as high as 70-100 % [47, 48, 52].

Usually, planting....

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Taro leaf blight is usually controlled by the use of copper fungicides at the rate of 38 $Lha^{-1}$ with 2.24 kg of copper oxychloride as an active ingredient. This application starts from four months after planting (MAP) to nine MAP, weekly during the rainfall period and bi-weekly when the conditions are dry. Dithane M-45 can also be used at the rate of

1.68-2.25 kg in 189.3-378.5 L water for a hectare. The application can be weekly or bi-weekly depending on the severity of the disease, but should not exceed 25 applications and it must be stopped when the crop is nine months old [47]. Metalaxyl fungicides have also been used for effective control of the disease [50]. In Hawaii, planting distance was used as a control measure and there was a resultant decrease in the disease incidence, and this was achieved by increasing the distance from 46 cm to 75 cm. In Solomon Island, sanitation through removal and pruning of infected leaves on a bi-weekly basis also reduced disease incidence.

The use of resistant and immune varieties is the most viable control measure for TLB in terms of environmental impact and sustainability [44, 53-58]. However, the use of resistant varieties has been limited due to lack of crop improvement programs or desirable economic market value traits in the resistant genotypes. This is coupled with a lack of knowledge in understanding the genetic structure of pathogen populations [57]. As compared to other species of *Phytophthora*, very little attention has been paid to *P. colocasiae* globally or at the regional level. Some research has been carried out on screening for disease resistance genotypes and their adaptability in West Africa and beyond. For example, Ackah *et al*. [58] evaluated taro genotypes from Ghana for resistance to TLB and found all the genotypes to be susceptible though to varying degrees. Similarly, Amadi *et al.* [59] characterized some local and exotic collections of taro for yield, local adaptation, and TLB resistance in Nigeria and found some promising genotypes, though no single one combined all the desired traits.

Compared to...
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Other major taro diseases are caused by viruses that reduce corm size and quality, with yield losses of up to 20% being reported [42]. Taro bacilliform virus (TaBV) is a badnavirus that results in a range of mild symptoms including stunting, mosaic, and curling of leaf blades. However, co-infection of taro with TaBV and Colocasia bobone disease virus (CBDV) is thought to be lethal to the crop. The presence of several other taro viruses currently restricts the international movement of germplasm, thus many countries do not have the access to agronomically elite genotypes and selected traditional cultivars. Some other taro diseases include the taro soft rot, caused by several species of *Pythium*, which is soil-borne and attacks the roots and corms. Sclerotium rot is caused by *Sclerotium rolfsii*, which causes stunting of the plant, rotting of the corm, and formation of numerous sclerotia in the corm. Cladosporium leaf spot is caused by *Cladosporium colocasiae* where brown spots appear on the older leaves. Among pests, the taro beetle is of great concern as they feed on the growing corm under the soil leaving large holes in the corm thus reducing the market quality. Other insect pests include the taro leafhopper which transmits viruses and may cause wilting and death of the plant.

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These are Pacific diseases; please relate to Africa..:

e.g. is there a threat of introduction?

**7. Botany and Uses of Taro**

Taro is a herbaceous plant that grows to a height of 1-2 m. The plant consists of a central corm (lying below the soil surface) from which leaves grow upwards, roots grow downwards, while cormels and runners (stolons) grow laterally. The leaves are simple peltate, spirally arranged in a rosette (Figure 3). The petioles could reach about a meter in length, with each having a distinct sheath, a cordate blade of about 85 cm by 60 cm with rounded basal lobes, usually with three veins. Some prominent veins may arise from the three veins, but the overall leaf venation is reticulate (net-veined). The inflorescence is borne on a spadix with a sterile appendage at the tip, encircled by a spathe, and aided by a peduncle (Figure 4). Each plant may bear more than one inflorescence. It has protogynous unisexual flowers with fused stamens borne at the upper part of the spadix while the pistil is at the lower part, the stamens and pistils are separated by a row of sterile flowers. Each fruit is a berry consisting of numerous seeds, the shape of which range from an ovoid to ellipsoid, about 2 mm in length with an extensive endosperm. Pollination in taro is presumably accomplished by insects. Fruit set and seed production occur only occasionally under natural conditions. The average maturity of the plant ranges between 8 months to 12 months [29, 32, 60]. Corm formation starts about three months after planting

Incorrect description of inforescence.
The infl. is composed of an outer spathe and inner spadix borne on a peduncle.

The inflorescence as a whole is protogynous because the female flowers (on lower spadix) mature before the male flowers (upper spadix)

..average age at maturity (define maturity in new sentence preceding: e.g. for production purposes, the crop is considere mature when the fmother crom is fully expanded..)

while cormel formation follows soon afterward. In the dasheen types, the corm is cylindrical and large (Figure 5). It can grow up to 30 cm long and 15 cm in diameter constituting the main edible part of the plant. In eddoe types, the corm is small, globoid, and surrounded by several cormels (stem tubers) (Figure 6). Corms and cormels are similar in their internal structure with the outmost layer being a thick brownish periderm (Figure 5 and Figure 6).



**Figure 3.** Taro plant with leaf patterns.



. Figure 4. Taro flower .




**Figure 5.** Taro Corm (Dasheen type.



**Figure 6.** Taro Corm (Eddoe type).

Cite relevant sources more frequently in relation to specific areas of information, not just at the end of a paragraph that covers multiple topics.

The main economic parts of the taro plant are the corms and cormels, as well as the leaves. Taro corms are an essential food in the diet of Africans, eaten in a variety of ways (boiled, fried, roasted, as porridge) and used as food additives. The leaves are used as a vegetable and are a good source of vitamins, especially folic acid. It contains 23% protein on a dry weight basis and is also a rich source of calcium, phosphorus, iron, vitamin C, thiamine, riboflavin, and niacin. The inflorescence is a delicacy in some food cultures of Asia and the Pacific. The corms and leaves are also used for medicinal purposes. Its fermented product is rich in probiotics, thus an amelioration for gastroenteritis, Crohn's dis-

ease, depressed immune function, and inadequate lactose digestion [61, 62]. Taro is gluten-free, making it suitable for people with gluten intolerance and the starch grains are minute, making it highly digestible (99%). It is a good source of calcium for children who cannot take milk due to lactose intolerance [5, 29]. It is also used as a curative for arterial hypertension, liver infections, rheumatism, and snake bites [29, 61, 63]. The corm can be used to prepare nutrient media for nematode growth [64]. Taro can also be used to produce biofuel [65, 66] and biodegradable plastics [67]. The mucilage serves as a good carrier for drug administration [68]. The resilience of taro makes it a good alternative crop when other crops fail under extreme weather conditions [41, 69]. Taro peels and wastes can be used as animal feed [29]. It can be also used as an ornamental plant [15, 63, 65].

63, 66 may be secondary sources in relation to ornamental taros

## 8. Taro Improvement

Taro is widely cultivated by resource-poor farmers in different ecological conditions of tropical and sub-tropical regions of the world, however, the largest area of cultivation is in West Africa, which accounts for the majority of output [70, 71]. It has been cultivated for more than 20 decades and remains an important crop to several cultures in Asia, the Pacific, and Africa but still lacks international recognition [5, 61, 72, 73]. Additionally, there is no international center that maintains taro germplasm, and is usually maintained by the national institutes with limited facilities and several challenges. The crop is also understudied when compared with other staple crops like maize, wheat, rice, cassava, and potato.

Give attention to dates! "20 decades"
is odd expression an means only 200 years. Delete as antiquity of the crop has been covered in first paragraph and is much more than 200 years.

The success of taro improvement depends strongly on genetic resources. Although taro is a vegetatively propagated crop, the availability of genetic diversity in existing germplasm collections on farmers' fields is extremely high. This is coupled with a lack of information on characterization data and the availability of a database where all information can be centrally located. The main challenge for breeders is to source genetic resources specific to traits such as resistance/tolerance to leaf blight, viral diseases and taro beetle, morphology, and quality traits. Present breeding programs are generally led by national institutes, and international collaboration among breeders and a standard procedure for germplasm exchange is not fully established. The situation is not different in the West African region. In fact, taro breeding in the region has not exceeded the conventional means [30, 58, 59, 74, 75]. Some information on germplasm characterization is available and promising genotypes have been identified for resistance to the TLB disease and adaptability to the local environment. However, the major constraints ~~for a consistent taro breeding program in the region~~ have been the lack of concerted interest in the crop by plant breeders, inadequate funding from national or international agencies, ~~and taro as a priority crop in the countries/region~~ and inadequate research infrastructure [76]. In addition, there are several bottlenecks in the biology of taro that retards progress in improvement for disease resistance and agronomic performance [30, 32]. There is a need to establish national/regional interest in this crop for concerted efforts on germplasm collection, conservation, maintenance, characterization, and initiate breeding programs to facilitate the development and release of improved cultivars, and revive taro production in the region. This is notwithstanding the fact that even with challenges, there has been extensive research on taro in the Pacific region, Oceania, and Asia leading to the release of two improved varieties with improved disease resistance, and good agronomic and culinary attributes [5, 27, 56]. There are several factors necessary for taro improvement and these are:

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unclear sentence; specify Africa?

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### *8.1. Taro Germplasm Collection and Conservation*

Germplasm collection and documentation are necessary for effective conservation, management, and utilization of plant genetic resources. It is well known that many genotypes/landraces of taro are scattered in diverse environments and their conservation, genetic diversity status, and improvement through breeding strategies are not fully documented. Therefore, it becomes necessary to generate knowledge of genetic variability among the existing germplasm that can help in developing conservation and breeding strategies for further improvement and utilization of the genetic resources. Several

Summarise more briefly, then note the connections made with Africa (reports of introduction of resistant breeding stocks to Africa from the Pacific).

germplasm collections have been established in several countries in Asia and the Pacific as part of the Taro Network for Southeast Asia and Oceania (TANSAO). These collections have been fully characterized using internationally standard morphological descriptors [77] providing a definite picture of the extent of genetic diversity within that geographical region [78]. In addition, currently, The Centre for Pacific Crops and Trees (CePaCT) maintains the largest taro collection (1136 accessions) comprising germplasm majorly from the Pacific and Southeast Asia. The taro collection in CePaCT was established following botanical expeditions by several organizations to gather crop wild relatives of taro from their various centers of origin [79]. This parental material was used in breeding to produce TLB-resistant varieties. Most taro collections are maintained as field collections, although some are also maintained as *in vitro* collections [80]. According to the World Information and Early Warning System (WIEWS) on Plant Genetic Resources for Food and Agriculture, a total of 1685 taro (*Colocasia* spp.) accessions were conserved *ex situ* in 2017 by 14 institutes (Table 1) [81]. In addition, a total of 2199 taro accessions were collected within the *TaroGen* (Taro Genetic Resources: Conservation and Utilization) project representing 10 countries in Oceania, maintained as *ex situ* collections at national level [82]. While taro germplasm collection and genetic diversity has been documented at the country and regional levels in Asia and the Pacific, few reports of such germplasm collection and maintenance are available from Americas and Africa, where it has been introduced through human migrations.

**Table 1.** Global taro (*Colocasia* spp.) genetic resources conserved ex situ in 2017, based on WIEWS.

| ***Country*** | ***Holding institute code*** | ***No. of accessions*** | ***Mode of conservation*** |
|---|---|---|---|
| Cuba | CUB006 | 112 | Field |
| Ecuador | ECU023 | 18 | Field |
| Ethiopia | ETH085 | 138 | Field |
| Fiji | FJI049 | 1165 | *In vitro* |
| Guyana | GUY021 | 8 | Field |
| Japan | JPN183 | 29 | Field |
| Malawi | MW1041 | 111 | Field |
| Malaysia | MYS220 | 47 | Field + *in vitro* |
| Panama | PAN172 | 1 | *In vitro* |
| Peru | PER045 | 6 | Field |
| South Africa | ZAF062 | 35 | Field[a] |
| Spain | ESP172 | 3 | Field |
| Swaziland | SWZ015 | 11 | Field |
| Taiwan | TWN001 | 1 | Seed |
| Total | | 1685 | |

As vegetative propagation and fixation of somatic mutations are common in taro, cultivars/genotypes can be distinct in morphotype even within the same genetic background [83]. This characteristics of taro makes it necessary that the landraces from countries within West and Central Africa (Nigeria, Ghana and Cameroon) and other countries in Africa are collected, characterized and conserved for further utilization in its improvement.

*8.2. Taro Germplasm Characterization*

There is information available on taro germplasm characterization using morphological traits and molecular markers. As a species, taro is highly polymorphic [84] for phenotypic traits such as size of corms and number of cormels. Singh *et al.* [85] reported high variability among 859 taro accessions from Papua New Guinea using 10 quantitative and

20 qualitative traits. High morphological variability has been also reported among taro accessions from Southeast Asia and Oceania [86, 87]. Similar agromorphological variability was observed among 2,298 taro accessions collected within TaroGen project [88]. In Ethiopia, morphological variability was observed among taro accessions, while the existence of wild type taro was also reported [89]. On the other hand, limited variability was reported among five taro cultivars in Nigeria [90]. Several molecular techniques have also been used for characterization of taro in the Pacific and Asia like isozymes [5], amplified fragment length polymorphism (AFLP) [2], microsatellites [8. 91], and inter-simple sequence repeat (ISSR) [55]. Chaïr *et al.* [8] reported variability among 357 taro cultivars from 19 countries in Asia, the Pacific, America and Africa using microsatellites and suggested that most taro genotypes grown in West Africa originated from India. Although high morphological variability was observed among 2,298 taro accessions collected from seven countries within *TaroGen* project, however, Lebot *et al.* [88] reported narrow genetic base among these accessions based on isozymes and AFLP fingerprinting. The genetic diversity of a clonally propagated crop like taro is expected to be narrow, especially in countries where it was introduced through vegetative propagules. This narrow genetic base not only makes the crop extremely susceptible to biotic stresses like TLB disease but also to abiotic stresses. Collecting and conserving the existing wild and cultivated genetic diversity in the countries of origin and sharing this diversity with producer countries in other parts of the world, in Africa, the Americas, and the Caribbean is a strongly recommended approach.

### *8.3. Taro Breeding*

Integrate this section with section 10?

"breeding" implies sexual reproduction, not all sexual crosses are hybrid crosses; use technical terms with more care for meaning

"successful" in what way, and what does "true seeds" refer to here?

The major objectives of taro breeding is to improve plant architecture (such as optimal number of suckers, absence of stolons, optimal number of leaves, etc.), corm yield, resistance/tolerance to diseases such as TLB, and quality traits (such as dry matter content, low levels of phenolic compounds causing irritation, etc.) [92]. Breeding activities with parents from diverse genetic base could result in improved targeted traits. However, taro is usually propagated through vegetative means, and rarely flowers, while the flowers are protogynous making conventional breeding methods difficult [34]. Taro breeding has been initiated in many countries within the South Pacific under two major programs, TaroGen and TANSAO [93]. These concentrated on sexual hybridization to develop new cultivars with higher yield, taste and resistance to TLB [94, 95]. Sexual hybridization of taro is promising, however, it is labor intensive and lengthy in terms of induction of flowering (gibberellic acid can be used to induce flowering in taro; [30, 49, 75] ), pollination and seed harvesting. It takes almost 10 years or more from pollination until a new improved cultivar reaches the farmers [96]. There is a scarcity of report on taro breeding in west Africa, and majority of the work is limited to agromorphological characterization or evaluation of local landraces. Nevertheless, Amadi *et al.* [30] made 109 crosses using 15 exotic cultivars of taro and four local cultivars in Nigeria, of which 18.3% were successful while nine crosses generated true seeds.

Application of biotechnological techniques for disease-free clonal propagation of taro plants is another viable option. Tuia [97] developed an efficient taro multiplication protocol and reported that it was possible to eliminate viruses using meristem culture. There are also reports of somatic emryogenesis in taro [98-100] but the regeneration rate was low. Similarly, Fukino *et al.* [101] reported transformation in taro (*C. esculenta* var. *antiquorum*) callus by particle bombardment wherein only two putative transgenic plants were obtained through particle bombardments. Transformation in *Colocasia esculenta* var. *esculenta* via microprojectile bombardment [102] and *Agrobacterium tumefaciens* [103, 104] has also been reported. These efforts showed that there is a possibility of using biotechnology to generate taro plantlets, however, there is a need to validate the vigor of plants in term of growth rate, pest and disease resistance and corm characteristics in addition to extensive field trials to record the frequency of somaclonal variations [105].

## 9. Opportunities for Improved Taro Production in West Africa

Among all root crops, taro currently has the lowest average yields (5.4 t/ha globally) [106]. West African countries dominated as the major producers of taro globally, with a total production of 4.9 million tonnes of the estimated 12.0 million tonnes of taro produced in the world [81]. In the same year, Nigeria, the world's largest producer of taro, harvested approximately 3.2 million tons from 0.8 million hectares followed by Ghana with 1.68 million tons of production [81]. Currently, there is no taro germplasm repository in the region responsible for preserving, characterizing, and distributing taro germplasm. The International Institute of Tropical Agriculture (IITA) in collaboration with the National Root Crop Research Institute of Nigeria (NRCRI) collected and preserved taro landraces. However, the collection was lost during the outbreak of taro leaf blight disease in West and Central Africa including Nigeria [20], Ghana [21], and Cameroon [107]. Breeding for resistant cultivars offers the best long-term control of taro leaf blight disease in most production systems. However, urgent and collaborative efforts among research groups and donors are needed to combat this epidemic and prevent taro from going extinct in the region.

In recent years scientists in WA and beyond have been gathering information, providing strategies and evaluating stress factors, to aid the improvement of the taro crop [8, 18, 30, 59, 61, 108-112]. Some of the improvements are as follows:

i) *Standardized Collection Protocols*: Dansi [110] wrote a book chapter on collection procedure for root and tuber crops with taro inclusive. The communication is a piece of synthesized information from publications of international bodies such as the Bioversity International, World Conservation Union (IUCN), the Food and Agricultural Organization of the United Nations, and the United Nations Environment Programme (UNEP). This is to ensure that collection missions are executed using international standard procedures.

ii) Characterization of local and exotic germplasm for agromorphological traits, disease resistance, and nutritional qualities as the basis for taro improvement: Several authors have used morphological characterization to evaluate taro cultivars including agromorphological traits, diseases, flowering ability, and others [59, 75, 111, 113]. This has helped to classify taro into different morphotypes which can be further used in the taro improvement programs.

There is still more to be done with taro in WA. There is a scarcity of information on the use of molecular techniques in the characterization of taro, which could facilitate understanding of the genetic phylogeny of local accessions and fast-track the improvement of the crop. In addition, there is a need for raising the awareness among different stakeholders, including producers and consumers, about the crop's potential contributions to food security, health, and economics so that the improved production of the crop is prioritized in the region or the countries within the region.

## 10. Breeding Efforts in Taro

acridity is a positive attribute; farmers depend on it for crop self-defence; acridity levels of different cultivars need assessment so that consumers can apply suitable known cooking methods

Taro breeding efforts should focus on traits that are important for both producers and consumers such as yield, pest and disease resistance, nutritional quality, shelf life, plant architecture, maturity, and culinary characteristics [114]. Participatory breeding that involves different stakeholders can be followed to gather more information and adoption of new technologies. There is a need for a reduction in acridity in the taro corms to increase taro edibility.

Breeding in taro was initiated in the late 1970s and varieties were released in Fiji (1978), Samoa (1982; 1996), Solomon Islands (1978; 1992), Papua New Guinea (1993), and India (1995) [115, 116]. The first successful controlled hybridization of taro in Nigeria was reported in 2015 [30]. Breeding schemes such as bi-parental crossing and recurrent selection were used at an early stage of plant development for traits such as taro corm flesh and corm fiber colors, which were correlated with the color of different petiole zones [117]. There have been several efforts in Papua New Guinea for resistance breeding, and one of the difficulties was to get rid of deleterious traits from wild types. The limited success with taro breeding can be linked to the weak institutional capacities of most national institutes engaged in breeding coupled with lack of genetic resources and funding to estab-

lish a sustainable taro breeding program in West Africa. There is also need for consolidation of existing national, regional and international network in optimizing breeding methodologies for taro.

## 11. Constraints to taro breeding

### *11.1. Variation in ploidy and chromosome number*

Cytological studies on taro indicate confusion over the basic chromosome number. Various cytotypes have been observed with 2n = 28 (diploid) and 42 (triploid) forms with basic chromosome number of 14 [118]. Reports have suggested that the chromosomes are prone to unpredictable behavior during cell divisions, thus the chromosome number per cell may not be uniform [119, 120]. From breeding perspective, the occurrence of polyploidy in taro may result to changes in cellular structures leading to irregular meiosis. Therefore, the viability of gemetes and zygotes is very low [121].

### *11.2. Poor flowering*

Taro genotypes flower rarely and flowering is majorly influenced by environmental, physiological, genetic and developmental conditions [122]. Cultivars or landraces are not stable with flowering and may have abnormalities with inflorescence structure, which are the main limiting factors for conventional hybridization.

crossing

### *11.3. Sexual ~~hybridization~~ and seed ~~sett~~* set

1938 data (ref 124) is old; breeding by taro is very common when plants are allowed to reach sexual maturity; often they are harvested before sexual maturity; this review should gather reports of flowering and breeding in Africa, as far as possible.

Sexual hybridization is labor intensive and takes time in terms of field preparation, planting of parents, induction of flowering using gibberellic acid (GA), pollination, development and maturation of fruits and seed harvesting [123]. In addition, the development of new, improved cultivars takes 10 years or more from the time pollination is effected. Difficulties in seed setting have also been observed, and ~~it is also believed that taro does not set viable seeds or does it very rarely~~ [124].

### *11.4. Narrow genetic base*

Taro production is extremely low in comparison to other root and tuber crops like cassava, sweet potato, and yams. This could have resulted in a narrow genetic base in West Africa for use in its improvement program. This is coupled with other limiting factors such as lack of improved varieties, lack of planting materials, pests and diseases, and limited research and information on available taro germplasm compared to other regions such as the Pacific. Introduction and evaluation of cultivars from other countries for adaptation to local production systems is a promising way to increase local variability, diversity, and improvement of taro.

### *11.5. Availability of uniform planting materials*

Variation in what? Variation in growth or yield?

The productivity of crops and taro in particular in farmers' fields depends on several factors including the type of planting materials, size of planting materials, population density, etc. The use of different types of planting materials or propagules such as stolons/suckers, corms, and cormels result in high intraclonal variation [32]. For uniformity in growth and production in farmers' fields, ~~it is necessary that~~ uniform planting materials and population densities are ~~used~~. required

### *11.6. Limited knowledge on genetic/genomic resources for accelerated breeding*

The breeding of improved cultivars is a complex process that requires adequate knowledge and experience in addition to the availability of genetic resources, and reliable characterization data on morphological traits as well as biotic and abiotic stresses along with quality traits. In the case of taro, there is currently limited knowledge, experience as well as information available for use in the accelerated breeding of this crop.

## 12. Taro Genome and Relevance to its Improvement

Recent developments in genomics have resulted in an increased understanding of the genome as well as specific pathways in different crop plants. In this context, the availability of a high-quality chromosome-level genome of taro is an important step [33]. A popular taro diploid cultivar from Jiangsu, China with a basic chromosome number of 14, Longxianggyu, was used. The assembled genome size was 2.41Gb with a contig N50 of 400kb and a scaffold N50 of 159.4Mb. On the basis of a phylogenetic tree based on 769 genes, it was reported that taro and *Spirodela polyrhiza* (duckweed) were on the same branch of the tree that diverged approximately 73.23 million years ago, and there were at least two whole-genome duplication events in taro separated by a relatively short gap. Similarly, a *de novo* taro genome assembly was carried out in a Hawaiian landrace 'Moi' which is a grandparent to cultivars used in TLB-resistant mapping population, and also because it is known for its agronomic qualities [56]. The haploid assembly was 2.45Gb with a contig length of 38Mb and scaffold N50 of 317,420bp. The sequenced data from the TLB resistant mapping population revealed 16 major linkage groups with 520 markers and 10 quantitative trait loci (QTLs) significantly associated with TLB disease resistance.

whole genome duplication in Araceae is discussed by Natalie Cusimano, Aretuza Sousa and S. S. Renner (2012). "Maximum likelihood inference implies a high, not a low, ancestral haploid chromosome number in Araceae, with a critique of the bias introduced by 'x'." Annals of Botany 109: 681-692.

Is this deep evolutionary history in Araceae relevant to the present review?

These sequencing information is already helping researchers to understand how different traits are regulated in taro. Transcriptome sequencing in taro revealed the mechanism of purple pigment formation [125] and the development of EST-SSR [126], and SSR markers [127]. In addition, deep sequencing of taro transcriptome revealed major metabolic pathways of starch synthesis and helped in identifying the mRNAs and genes that are expressed for starch biosynthesis in taro corm [128]. Similarly, Dong *et al.* [129] conducted a comprehensive whole transcriptome sequencing in taro corms aged 1, 2, 3, 4, 5, and 8 months old to assess the starch and sucrose biosynthesis pathway. This study provided valuable resources for future exploration of molecular and physiological mechanisms behind the starch and sucrose properties of taro corms.

The molecular information will aid its improvement using genomic assisted breeding (GAP). The availability of the taro genome will inform studies on the origin, evolutionary history, and breeding of this crop. This will also aid in understanding molecular mechanisms underlying some of the key traits including diseases and quality traits. The QTLs identified for TLB disease can be further investigated to identify the genes contributing to resistance and the flanking markers can be used in marker-assisted breeding. Most importantly, a lot of ~~genomic resources such as~~ SSRs and SNPs can be ~~generated f~~or routine genotyping ~~in taro for~~ parental identification, assessment of genetic diversity, identification of duplicate genotypes, linkage mapping, QTL identification, and other genomic-assisted studies.

identified

s (pl.)

## 13. Future Perspective for Taro in West Africa

Taro is an important food and income security crop for millions of farmers in West Africa, particularly in Nigeria. One of the major challenges for sustainable crop production is genetic erosion of germplasm resources, and this is true in the case of taro since most of the germplasm is held in farmers' fields and in the wild. This poses a serious risk with the loss of valuable genetic resources and thus threatens taro sustainability in the region. There is a need to explore, collect and safeguard the existing genetic diversity as well as define the production zones to ensure better sustainability of the crop. Collection of germplasm representing the genetic diversity followed by effective conservation and utilization is a prerequisite for the success of taro breeding programs. There is a need to establish a regional and international network to strengthen the capacities of NARS breeding programs in different countries for germplasm conservation, utilization, and exchange. It will be interesting to introduce and evaluate a larger proportion of genetic diversity from Asia, the Pacific, and Latin America, following germplasm exchange protocols, so that different gene pools could be effectively combined to develop heterotic populations [130]. Such an approach is already being followed in cassava and maize breeding in Africa wherein germplasm from Latin America has been successfully introgressed into African germplasm [131]. The conventional taro breeding pipeline should target naturally occurring genetic resources as parents to improve traits such as disease resistance, quality,

Unclear expression and logic; are crop displacement (by other crops), disease and climate change threats to diversity of taro in Africa?

What does "resources" actually refer to here? Meaning unclear.

What resources, where?

etc., and ensure that those selected genotypes flower naturally or respond to induction of flowering through GA application. In addition, the newly developed cultivars should be tested in varying environments to take into account the genotype by environment (G x E) effect to simulate the large marginal non-optimal areas where taro is generally grown for its optimum yield performance. The participatory breeding methods also provide a good platform to identify superior cultivars, increase farmers' access to these cultivars, and help in broadening the genetic base for use in taro improvement programs. This needs to be coupled with the development of seed system strategies for the multiplication of disease-free planting materials, safe germplasm exchange, and a better distribution system for the dissemination of improved cultivars for sustainable production of taro in the region.

repeats previous statements

The application of molecular markers or next-generation sequencing methods plays an important role in crop breeding programs. In recent years, methods such as genotyping-by-sequencing (GBS) are applied to generate linkage maps and identify QTLs for TLB [56]. However, the use of such technologies has been limited and there is a need to use molecular genetic tools such as tissue culture and micropropagation; genotyping using SSRs or SNPs for assessment of genetic diversity, marker-assisted selection, genome-wide associations; identification of a set of markers for cultivar identification; etc. for taro improvement in West Africa. Future breeding programs should add value by including organoleptic characteristics and nutritional properties, widening export markets by generating value-added products, diversified uses, and promotion for consumption. ~~The industrial uses of taro include the production of flour, starch and non-starch products, biofuel, and other products to tackle post-harvest losses while improving food and income security.~~

This partly belongs to earlier section of review, and mixes topics. Unclear meaning

Most importantly, there is a need to develop a database on a number of cultivars at a national and regional level present in farmers' fields to keep track of genetic erosion in the crop. In addition, there is a need to generate information on agro-ecological production zones of taro in each country in the region while safeguarding the indigenous local knowledge following participatory methods. A Multi-disciplinary approach is needed in taro improvement and exploitation of its potential for better production and productivity through multi-environment evaluation under different agroecologies within each country.

Global initiatives such as the African Orphan Crops Consortium (AOCC) listed taro among the 101 traditional orphan or neglected crops of Africa that are important for food and nutritional security [132]. Taro has been neglected as a crop for research, and there is a need to prioritize taro as a crop of importance in the region and countries while investing in research funds effectively in the future.

AOCC is an important regional initiative; can more be said about it here or earlier in the review?

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