FRUITS 76(3), 123–133 | ISSN 0248-1294 print, 1625-967X online | https://doi.org/10.17660/th2021/76.3.3 | © ISHS 2021

Review

Towards domestication of the endemic Malagasy pepper *tsiperifery* (*Piper* sp.): Lessons learnt from domestication and cultivation history of other peppers

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Summary

Introduction – **Since the international popularity of *tsiperifery*, the Malagasy wild pepper (*Piper* sp.) from Madagascar started to grow, traditional low-intensity harvesting has turned into uncontrolled systematic collection, which is environmentally and socio-economically unsustainable. Domestication could be key for sustainable exploitation of *tsiperifery*. Here we collated information from comparable domesticated *Piper* species to identify pathways to accelerate the domestication of *tsiperifery*.** *Materials and methods* – **We conducted a literature review, upon four steps: (1) identification of the already domesticated *Piper* species; (2) analysis of their domestication history and cultivation methods to highlight the common critical points for domestication; (3) comparison of these information with the limited ones available on *tsiperifery*; and (4) provision of preliminary recommendations on a possible domestication pathway for *tsiperifery*.** *Results and discussion* – **We identified and analyzed 22 domesticated *Piper* species. We found nine critical issues, the most important being: (i) genotype selection; (ii) procedure for vegetative propagation; (iii) reproduction of the microclimatic and edaphic conditions of the rainforest understory; (iv) choice of the best supports and cultivation system; (v) reduction of the delay before entry into production; and (vi) control of plant height. For each critical issue, we suggested preliminary recommendations.** *Conclusion* – **This paper provides baseline information towards the domestication of *tsiperifery*. Further on-field and molecular experiments are needed to confirm these findings and identify suitable management practices.**

Keywords
agroforestry, Madagascar, non-timber forest product (NTFP), spice, sustainable exploitation, wild pepper

Significance of this study

What is already known on this subject?

- *Tsiperifery*, the wild pepper of Madagascar, is a new spice on the international market but it is threatened by environmental and socio-economic challenges. Domestication would be a promising option to achieve sustainable exploitation but is hindered by lack of information.

What are the new findings?

- This paper offers a review of the domesticated and semi-domesticated *Piper* species and summarises critical issues and recommendations useful for the domestication of *tsiperifery*. Domestication and cultivation of *Piper peepuloides* can be a promising model to follow.

What is the expected impact on horticulture?

- The domestication of *tsiperifery* will positively affect Madagascar Gross National Product (GNP) by increasing quantity and quality of production while protecting *tsiperifery* and endangered rainforest spots and providing an important income source to vulnerable forest dwellers.

Introduction

Tsiperifery is the endemic wild pepper of Madagascar, also known as *voatsiperifery*, its most common commercial name. Some Malagasy people have been using this spice traditionally for its culinary and therapeutic properties since very long time (Razafimandimby *et al*., 2017). In 2004, European celebrity chefs, in particular Olivier Roellinger and Gérard Vives (Couplan, 2009; Vives, 2010), discovered *tsiperifery* and triggered its import to Europe. Since 2010, *tsiperifery* has been the object of a growing demand on the international market. Today, it is a very popular product among European restaurant owners, chefs and spice merchants, who appreciate it for its peculiar organoleptic properties, its rarity and exotic origin (Razafimandimby *et al*., 2017).

To date, *tsiperifery* is considered a "wild" non-timber forest product (NTFP) (Ahenkan and Boon, 2011). Fruits are harvested in the wild by local forest dwellers, mainly in the natural forests of Angavo (since 2006) and Ankaï (since 2009) (Razafimandimby *et al*., 2017). Total export is estimated between 30 and 50 tons of dried fruits yearly (Razafimandimby *et al*., 2017), which is relatively small compared with other spices from Madagascar (Danthu *et al*., 2014). However, even this low amount already exceeds the production capacity of the exploited natural areas, promoting the expansion of

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the sector to new forest areas and threatening the long-term durability of the supply chain (Razafimandimby *et al*., 2017).

Since its popularity rise, traditional low-intensity sustainable harvesting of *tsiperifery* has turned into uncontrolled systematic collection, which endangers both *tsiperifery* and the whole rainforest (Razafimandimby *et al*., 2017). Forest dwellers no longer refrain from cutting the supports on which *tsiperifery* grows when they are too high to be climbed on to collect the bunches. Consequently, both the support and *tsiperifery* are killed, and the surrounding vegetation is damaged (Razafimandimby *et al*., 2017). In addition, the collection of both ripe and unripe fruits prevents the regeneration of the species (Razafimandimby *et al*., 2017). As such, a sustainable management strategy is urgently needed to prevent *tsiperifery* extinction and further environmental degradation.

On the socio-economic side, the main problem is the unfair distribution of the benefit of *tsiperifery* along the value chain (Razafimandimby *et al*., 2017). Dry *tsiperifery* retail price nears 200 € kg^{-1} in Europe and the U.S.A., but collectors, who belong to the poorest local people, only receive 2% of the product final value (Razafimandimby *et al*., 2017).

Presently, a consortium of Malagasy and French researchers within the partnership platform “Fôrets et Biodiversité”, is working on the sustainable exploitation of *tsiperifery* in Madagascar. Despite the initial enthusiasm generated by the study of Peters *et al*. (1989), the simple exploitation of NTFPs like *tsiperifery* by forest dwellers has failed in most cases to provide both a way out of poverty and efficient means to protect tropical forests from deforestation (Kusters *et al*., 2006). Exemplary cases are natural rubber (Danthu *et al*., 2016) and *Prunus africana* (Stewart, 2003; Jimu, 2011), two Malagasy NTFPs which have been exploited until they have been included in the CITES appendix II (CITES, 2016). On the other hand, according to Kusters *et al*. (2006), the household strategies that provide the best compromise between sustainable profitability and acceptable habitat degradation/conservation are all based on NTFP cultivation, either as a specialized crop or integrated in a diversified agricultural system. Therefore, we can consider domestication as the most promising solution also in the case of *tsiperifery*.

Domestication of *tsiperifery* aims at three distinct goals: (i) to improve the amount and the quality of fruit production hence ultimately to increase Madagascar Gross National Product (GNP); (ii) to protect *tsiperifery* and the associated forestland; and (iii) to provide a source of income to vulnerable forest dwellers. For what concerns the third aim, cultivation and harvest of larger amounts of peppercorns would increase the negotiating power of farmers, who may get a better price, especially through collective negotiation and control of the post-harvest process. Positive effects on prices for farmers are also expected by higher quality of the product, which can be obtained through genotype selection and the definition of standard protocols for cultivation, harvest and post-harvest treatments (Razafimandimby *et al*., 2017). The final aim for *tsiperifery* domestication is to achieve each of the three above-mentioned goals. However, technical options of the domestication process may favour one of these goals over the others. For instance, highly productive clone selection may contribute to increase production but would reduce biodiversity. Low-tech extensive cultivation systems may promote adoption by the poorest farmers but would have a limited contribution to production increase.

Unfortunately, domestication of *tsiperifery* is not an easy task. Domestication of a wooden species is a long-term and complex procedure that requires considerable knowledge on the domesticated species (Razafimandimby *et al*., 2017). In the case of *tsiperifery*, the task is even harder given the scant information available on the biology and ecology of the species. We cannot afford to wait for results from long-term studies to save *tsiperifery* (Razafimandimby *et al*., 2017); however, the domestication process may be accelerated by anticipating short-term suboptimal solutions. Domestication of pepper species has occurred in the past. Information on previous domestication processes and on the associated cultivation recommendations for similar species could suggest key points for the domestication of *tsiperifery*. The objective of this paper is then to identify the potential critical issues of *tsiperifery* domestication, building upon the limited information available for this species and on that available for comparable domesticated pepper species.

Through a bibliographic review, we retrieved peer-reviewed articles and books about domesticated *Piper* species, after verifying their scientific names and botanical characteristics in the online databases The Plant List (http://www.theplantlist.org) and Tropicos (http://www.tropicos.org). We used a four-step approach: (1) identification of the already domesticated *Piper* species; (2) analysis of their domestication history and cultivation recommendations to highlight the common critical points; (3) comparison of the collected information with the limited knowledge available on *tsiperifery*; and (4) provision of preliminary recommendations on how the *tsiperifery* domestication process may be undertaken.

Domesticated and semi-domesticated *Piper* species

This section provides a short overview of the domesticated *Piper* species found in the bibliographic review, other than *tsiperifery*. Although black pepper (*Piper nigrum* L.) is the only economically important pepper, humans exploit many other pepper species at different levels of domestication. Domesticated species are morphologically and genetically distinct from their wild ancestors because of artificial selection, and they cannot survive outside of cultivation. Semi-domesticated species are cultivated crops subjected to conscious artificial selection pressures, however, they are still not clearly morphologically or genetically distinct from their wild counterparts, which are often still harvested to give the same product (Meyer *et al*., 2012). In this review, we identified 22 domesticated *Piper* species (Table 1). Twelve of these species are at an advanced stage of domestication or semi-domestication, and are briefly described in the following paragraphs. The remaining ten species (*P. amalago*, *P. baccatum*, *P. decumanum*, *P. febrifugum*, *P. fragile*, *P. longifolium*, *P. pinnatum*, *P. ribesioides*, *P. stylosum*, and *P. subbullatum*) are minor species at a very early domestication stage, for which few information is available (Utami and Jansen, 1999).

Black pepper (*Piper nigrum* L.) is the most economically important species of pepper. It is a domesticated crop with more than 100 different cultivars (Ravindran and Kallupurackal, 2012). Its dried peppercorns represent one of the most important spices in the world in terms of overall value and trade volume (Van Wyk, 2014). Black pepper is a perennial woody vine native to Western Ghats of Kerala, India (Zeven, 1976; Waard and Anunciado, 1999; Thangaselvabal *et al*., 2008; Lim, 2012b; Ravindran and Kallupurackal, 2012). It was already domesticated in India in 3000 BC (Nair, 2011) and it is nowadays cultivated also in East Asia, Africa and South America.

Other *Piper* species cultivated for their peppercorns are *Piper cubeba* L.f. (cubeb pepper), *P. longum* L. (long pepper), *P. retrofractum* Vahl (Javanese pepper) and *P. guineense* Schumach. & Thonn (Ashanti pepper). *Piper cubeba* and *P. retrofractum* are native from Indonesia (Utami and Jansen, 1999; Lim, 2012a, c), while *P. longum* is native from India (Utami and Jansen, 1999; Ravindran *et al.*, 2012). The three species are now cultivated in several countries of South and South-East Asia (Utami and Jansen, 1999; Lim, 2012a; Ravindran *et al.*, 2012). Instead, *Piper guineense* originates from Western Africa (Van Wyk, 2014). During Ancient Greece and Rome and in Middle Age, *P. cubeba*, *P. longum* and *P. guineense* were important spices traded to Europe. Nowadays, black pepper has surpassed them, but they are still commonly used in Asian and African cuisine (Utami and Jansen, 1999; Weiss, 2002; Lim, 2012a; Ravindran *et al.*, 2012; Van Wyk, 2014). These four species are all perennial vines usually grown in home gardens and are still found in the wild (Utami and Jansen, 1999; Prapajati, 2003; Lim, 2012a).

Piper cubeba and *P. longum* are also cultivated as companion crops in cocoa (*Theobroma cacao* L.), coffee (*Coffea arabica* L.) or areca palm (*Areca* spp.) plantations (Utami and Jansen, 1999; Weiss, 2002; Lim, 2012c). *Piper longum*, *P. retrofractum* and *P. guineense* are also collected in the wild (Utami and Jansen, 1999). *Piper cubeba* and *P. longum* are domesticated species, while *Piper retrofractum* and *P. guineense* are at a semi-domesticated level.

Betel (*Piper betle* L.) is a climbing shrub from South and South-East Asia. It is a component of the so-called betel quid or *paan*, a traditional chewing stimulant mixture consisting of pieces of areca nut (seeds of the palm *Areca* spp.) wrapped in betel leaves (Teo and Banka, 2000). The betel quid is served in social, cultural and religious occasions such as weddings, religious festivals, and to welcome guests (Guha, 2006). Betel probably originated from Malaysia; it was domesticated more than 2,500 years ago, as it is already mentioned in the Vedas and Ayurveda (Teo and Banka, 2000; Annamalai *et al.*, 2016). Nowadays, it is cultivated in most of South and South-East Asia, both in dedicated plantations or as intercrop in coconut and areca palm plantations (Teo and Banka, 2000), and is a completely domesticated species.

Piper methysticum G. Forst. (kava) is a pepper species from the Western Pacific. Its roots used to produce a mildly intoxicating beverage, also called kava. Kava is a traditional drink in the Pacific culture, used in social and religious ceremonies like births, marriages, deaths, or to welcome guests (Singh, 2004). Kava was domesticated some 3,000 years ago and it has hundreds of different modern cultivars (Singh, 2004). This shrub is commonly found in the home gardens of most of the Pacific islands (Singh, 2004).

Piper angustifolium Lam. (matico or *hierba del soldado*) and *Piper aduncum* L. (spiked pepper) are two very similar pepper species from Latin America that are sometimes confused (The Plant List, 2012a, b). Their leaves are used in local traditional medicine, whose treelets can be cultivated or can occur in the wild (Prajapati, 2003; Padmanaba, 2016). Nowadays, *Piper aduncum* is considered an invasive weed in Indonesia, the Pacific islands, Hawaii and Florida (Starr *et al.*, 2003; Hartemink, 2006, 2010; Padmanaba, 2016).

Piper auritum Kunth (*hoja santa* or *hierba santa*) is a pepper species from tropical Mesoamerica, while *Piper sarmentosum* Roxb. (*la lot*) comes from East Asia (Prapajati, 2003). Leaves from both species are used to wrap meat and other food in the local cuisine (Tucker *et al.*, 2009; Ravindran *et al.*, 2012). These shrubs can be cultivated but also occur in the wild. *Piper auritum* is considered an invasive weed in the Pacific Islands and Hawaii (Denslow and Nelson, 2000; Narayanswamy, 2013).

Finally, *Piper peepuloides* Rox is a wild pepper from Meghalaya (Eastern Himalayas) in India, whose peppercorns are used as a spice or in Ayurvedic traditional medicine (Tynsong *et al.*, 2013). The case of *P. peepuloides* is a nice example of how it is possible to achieve a certain level of domestication in a relatively short time, and its domestication process can be considered an interesting model for *tsiperifery*. This wild pepper was traditionally harvested in the wild, but it has been recently domesticated by local populations in areca nut and betel leaves agroforests in order to meet a growing market demand (Tynsong *et al.*, 2013). Its domestication has also proved to have positive outcomes on both the income of local people and forest biodiversity, which is also the goal of *tsiperifery* domestication. However, it is important to mention that for this species mass cultivation has been impossible, because of specific requirements in terms of high rainfall and altitude range that can only be found in few locations along its original habitat (Tynsong *et al.*, 2013). As a wild pepper, *tsiperifery* could have similar production limitations.

Biology and ecology of *tsiperifery*

Tsiperifery is a generic name used to indicate more than one similar species belonging to the *Piper* genus (Piperaceae) (De Candolle, 1923; Decary, 1946; Manjato *et al.*, 2010). Its last formally accepted scientific names are *Piper borbonense* C. DC, *Piper pyrifolium* Vahl and *Piper pachyphyllum* Baker (De Candolle 1923), but they are currently under revision (Razafimandimby *et al.*, 2017). Recently, Palchetti *et al.* (2018) described two new wild pepper species found in Madagascar as *P. malgassicum* and *P. tsarasotrae*, and claimed that, together with *P. borbonense*, they are likely to constitute what is commonly known as *voatsiperifery*. The identity of the two new species was verified by comparing them with the most closely related *Piper* species using a Principal Component Analysis on 22 morphological characters (*e.g.* stem nodes, leaf length, number of stigma, *etc.*) and performing a phylogenetic analysis with maximum likelihood based on *trn*L intron, *ndh*F, and *G3pdh* genes. We contend that while the claimed identity may be true in the case of *P. malgassicum*, a species found in humid forests, it is unlikely that *P. tsarasotrae* belongs to the *tsiperifery* species complex because it is typical of dry forest areas. Anyway, their work had the merit to match the use of classical phenotypic (morphologically-based) analysis with molecular approaches. Molecular approaches are increasingly used to describe challenging genera with vast number of species with similar morphology (such as *Piper*) (Wojciechowski et al., 1999; Berry et al., 2005; Weese and Bohs, 2007; Jaramillo *et al.*, 2008). Palchetti *et al.* (2018) claimed that these approaches could be useful as a bar-coding method for the identification and traceability of spice and drug traditional mixtures. In the case of *tsiperifery*, further molecular analyses are required to provide accurate classification of the species and describe its phylogenetic relationship with similar species within the genus *Piper*.

Tsiperifery is a liana (Figure 1) that thrives all along the evergreen forests in eastern Madagascar (Razafimandimby *et al.*, 2017). It is a typical species from primary forest but can be also found in secondary forests. As a rainforest species, the most important ecological parameters for its survival are the presence of forest canopy, high average annual temperature and minimum precipitation of the driest month

TABLE 1. List of domesticated and semi-domesticated pepper species (*Piper* sp.) with key information.

Scientific name	Common name	Habitus	Centre of origin	Cultivation area	Main use	Part of plant	Cultivation system	Domestication time	Domestication level
Piper nigrum L.	Black pepper	Woody climber	Western Ghats in Kerala (India)	India, South-east Asia, Africa, South America	Spice	Peppercorns	Unshaded intensive plantation, intercrops in shaded plantations, home gardens	Before 3000 BC	Fully domesticated
Piper cubeba L.f. (accepted name *Cubeba officinalis* Raf.)	Cubeb, cubeb pepper, Java/Javanese pepper, tailed pepper.	Woody climber	Great Sunda Islands (Indonesia)	Indonesia, India	Spice	Peppercorns	Intercrops in shaded plantations, home gardens	Before ancient Greece and Rome	Domesticated. Still occurring in the wild
Piper longum L. (synonym *Chavica roxburghii* Miq.)	(Indian) long pepper, *pipeli*	Woody climber	North-east India and Nepal	India, Indonesia, Malaysia, Sri Lanka, Singapore; southern Philippines	Spice	Peppercorns (whole infructescence is used)	Intercrops in shaded plantations, home gardens	Before ancient Greece and Rome	Domesticated. Also gathered in the wild
Piper retrofractum Vahl (synonyms *Chavica officinarum* Miq., *Piper chaba* Hunter, *Piper officinarum* (Miq.) C.DC.)	Java/Javanese (long) pepper	Woody climber	Indonesia, Malaysia, Philippines, Thailand, Vietnam	Java (Indonesia), southern China	Spice	Peppercorns (whole infructescence is used)	Home gardens		Semidomesticated. Mostly gathered from the wild
Piper guineense Schumach. & Thonn.	West African pepper, Ashanti pepper	Woody climber	West Africa	West Africa	Spice	Peppercorns	Home gardens	Before ancient Greece and Rome	Semidomesticated. Mostly gathered from the wild
Piper betle L.	Betel	Woody climber	Malaysia	Sri Lanka, India, Thailand, Bangladesh, other countries in South-east Asia	*Paan* (traditional chewing stimulant mixture)	Leaves	Intercrops in areca palm plantations or dedicated plantations	More than 2500 years ago	Fully domesticated
Piper methysticum G. Forst.	*Kava* (*kawa*, *'ava*, *'awa*), *kava-kava* (*kawa-kawa*, *'ava-'ava*, *'awa-'awa*), *yaqona*	Shrub	Vanuatu	Pacific Islands	*Kava* (traditional mildly intoxicating beverage)	Root	Home gardens	3000 years ago	Fully domesticated
Piper angustifolium Lam. (accepted name *Piper consanguineum* (Kunth) Steud.)	Matico, *hierba del soldado* (soldier's herb)	Shrub	Peru, Bolivia, Ecuador	South America	Local medicine	Leaves			Semidomesticated. Also occurring in the wild
Piper aduncum L. (synonym *Artanthe adunca* (L.) Miq.)	Spiked pepper, false matico, false kava	Shrub	South and Central America	South and Central America	Ornamental, local medicine	Leaves			Semidomesticated. Also occurring in the wild. Invasive species in Indonesia, the Pacific Islands, Hawaii and Florida

TABLE 1. Continued.

Scientific name	Common name	Habitus	Centre of origin	Cultivation area	Main use	Part of plant	Cultivation system	Domestication time	Domestication level
Piper auritum Kunth	*Hoja santa* (sacred leaf), *hierba santa* (saint herb), Mexican pepper leaves, root beer plant	Shrub	Southern Mexico, Panama, Guatemala, Northern Colombia	Mesoamerica (Central America)	Local cuisine	Leaves and young stems			Semidomesticated. Also occurring in the wild. Invasive species in the Pacific Islands and Hawaii.
Piper sarmentosum Roxb. (synonym *Piper lolot* C. DC.)	Lolot pepper, *lalot*, wild betel leaves	Shrub with creeping stems	East Asia	Cambodia, China, India, Indonesia, Laos, Malaysia, Philippines, Vietnam					Semidomesticated. Also occurring in the wild
Piper peepuloides Roxb. (unresolved name)	Wild pepper	Woody climber	Meghalaya in the Eastern Himalayas (India)	Meghalaya (India)	Spice	Peppercorns	Areca palm and betel leaves agroforests	Last decades	Semidomesticated. Also gathered from the wild
P. baccatum Blume		Climber	Java, Borneo, Philippines		Local medicine, spice, juice	Berries, leaves			Very early domestication stage
P. decumanum L.		Climber	Philippines, Sulawesi, Moluccas and New Guinea		Local medicine	Berries			Very early domestication stage
P. febrifugum C. DC. (unresolved name)		Climber	Peninsular Malaysia		Local medicine	Leaves			Very early domestication stage
P. fragile Benth.		Climber	Philippines, Moluccas, New Guinea and Solomon Islands		Local medicine	Berries			Very early domestication stage
P. longifolium Ruiz & Pavón.			Tropical America		Local medicine				Very early domestication stage
Piper amalago L. (synonym *P. medium* Jacq.)			Tropical America		Intoxicating beverage				Very early domestication stage
P. pinnatum Lour. (unresolved name)			Indo-China		Washing clothes				Very early domestication stage
P. ribesioides Wallich.			Burma (Myanmar), Peninsular Malaysia and Sumatra		Local medicine	Leaves			Very early domestication stage
P. stylosum Miq. (unresolved name)			Malaysia, Sumatra and Borneo		Vegetable (leaves), local medicine (roots)	Leaves, roots			Very early domestication stage
P. subbullatum K. Schum. & Lauterb. (unresolved name)		Shrub	Philippines, New Guinea, Bismarck Archipelago, Solomon Islands and Vanuatu		Local medicine	Leaves			Very early domestication stage

FIGURE 1. An individual (liana) of *tsiperifery* climbing on its tree support; primary rainforest near Anorana, central Madagascar (Photo: P. Bàrberi).

(Razafimandimby, 2009). *Tsiperifery* is a light-avoiding species: it lives under a dense forest canopy (70–90% shade) and usually prefers northward or eastward sides. According to Razafimandimby (2009), it cannot survive if there are too many openings in the canopy such as those found in degraded forests. *Tsiperifery* needs a high rate of relative humidity (at least 50–70% RH during the day and 95% RH at night) (Ratsaraefatrarivo, 2012). As a hygrophilous species, it grows near water sources or in water-saturated soils (Ratsaraefatrarivo, 2012). For this reason, it is especially common in valleys and other lowland areas where water accumulates (Razafimandimby *et al.*, 2017).

Tsiperifery can use almost every type of support (trees, shrubs, tree ferns, dead trees, rocks, *etc.*) but it prefers straight supports without lateral branches (Touati, 2012). Since it grows up to 15–25 m, it prefers to climb on large trees. Usually, the creepers do not jump between potential supports but propagate from shoots crawling on the ground. *Tsiperifery* is characterized by clear leaf dimorphism: the vegetative orthotropic stems bear cordate leaves, while the reproductive plagiotropic stems bear elliptical to oblong leaves (Razafimandimby *et al.*, 2017). Plagiotropic stems appear during the second year when the vine has reached the height to flower (8–25 m) (Touati, 2012). Fruiting is stimulated by 60–75% shade that is achieved when the individuals reach the upper part of the forest canopy (Razafimandimby, 2009). The plant is dioecious hence male and female flower spikes occur on separate individuals (Razafimandimby *et al.*, 2017). The fruits are small berries, which become red at maturity. *Tsiperifery* has a minor fruiting peak in June-July and a major one in September-November, but individual plants bear fruits only once a year (Razafimandimby *et al.*, 2017). Infructescences are typically composed of fruits at different stages of ripeness, where some of the berries never ripe completely (Razafimandimby *et al.*, 2017). *Tsiperifery* is also characterized by the phenomenon of alternate bearing, which varies considerably among individual plants, giving a berry production from 1 to 25 kg plant^{-1} (Touati, 2012). *Tsiperifery* mostly reproduces vegetatively: orthotropic vegetative stems claw from the collar to find new tree supports to climb on. However, its global regeneration rate, as the percentage of young individuals over mature individuals, is around 140%, which is quite low considering that a rate of 300% is usually required for adequate regeneration for forest species in Madagascar (Razafimandimby, 2009).

Common critical issues for the domestication of *Piper* species

Despite the huge variety and the different levels of domestication of *Piper* species, it is possible to identify some common critical points that are of interest for *tsiperifery*. Here, we will focus on the twelve most important species (*P. nigrum, P. cubeba*, *P. longum*, *P. retrofractum*, *P. guineense*, *P. betle*, *P. methysticum*, *P. angustifolium*, *P. aduncum*, *P. auritum*, *P. sarmentosum,* and *P. peepuloides*), and especially on vines and species cultivated for peppercorns.

Genetic constancy, yield quantity and quality

The selection of cultivars with genetic constancy, high fertility (*i.e.*, potential yield) and high produce quality are the most important goals for the domestication of any wild species (Frankel and Galun, 1977). These have been completely accomplished for the fully domesticated *Piper* species (*P. nigrum*, *P. betle*, and *P. methysticum*) but are still ongoing in the other ones. Nowadays, hundreds of different cultivars of black pepper and kava are available (Singh, 2004; Ravindran and Kallupurackal, 2012).

In the case of *tsiperifery*, the selection of cultivars with such features would be fundamental. Wild individuals are morphologically unstable and have highly variable yield (Razafimandimby *et al.*, 2017). Moreover, the organoleptic quality of the product is also variable, which is a threat to the marketability of *tsiperifery* (Razafimandimby *et al.*, 2017). Indigenous knowledge (Ratsaraefatrarivo, 2012; Touati, 2012) and preliminary botanical studies (Raherinjatovoarison, 2017) led to the identification of several different types of *tsiperifery*. This interspecific diversity can be initially exploited, while awaiting results of dedicated genetic improvement efforts. However, cultivar selection is a very long process which may require qualified workers and technologies. Among cultivar selection approaches, clonal selection could be eventually implemented in low-technology and participatory programmes with farmers but the results would still require many years to be produced. As such, optimization of cultural practices seems more important in the short term and could be initiated before termination of the cultivar selection process. It is important to note that this selection process should focus on producing multiple cultivars instead of only one, in order to conserve genetic diversity and provide cultivars adapted to different regions.

Dioecy

Piper species from Africa and Asia (paleotropical species) are dioecious (wild *P. nigrum*, *P. cubeba*, *P. longum*, *P. retrofractum*, *P. guineense*, *P. betle*, *P. sarmentosum*) (Utami and Jansen, 1999; Prapajati, 2003; Greig, 2004; Guha, 2006; Thangaselvabal *et al*., 2008; Nair, 2011; Lim, 2012a, c). Dioecy is a problem for the cultivation of pepper species whose product are peppercorns because both female and male individuals are needed in the same plantation to produce fruits. In the case of black pepper, gynomonoecious or trimonoecious cultivars have been selected in order to have only one type of individuals on the same plantation (Thangaselvabal *et al*., 2008; Nair, 2011). In gynomonoecious cultivars female and hermaphrodite flowers occur on the same individual, while in trimonoecious cultivars female, male and hermaphrodite flowers occur on the same individual. On the contrary, *P. cubeba*, *P. longum*, *P. retrofractum*, and *P. guineense* are only dioecious, therefore plantations must include individuals of both sexes. A fixed species-specific ratio ensures the highest yield while minimising the number of unproductive male plants. For example, for *P. cubeba* the male:female ratio is about 1:9 (Utami and Jansen, 1999). In the dioecious *Piper* species, sex can be identified only after the first flowering, and surplus male plants are usually removed afterwards (Utami and Jansen, 1999).

As a paleotropical species, *tsiperifery* is dioecious. Since the selection of monoecious cultivars is not possible in the short term, presently both male and female individuals are needed in the same plantation. The optimal male:female ratio should then be defined, possibly using that of *P. cubeba* as a starting point. In the long term, research should investigate the existence of gynomonoecious or trimonoecious individuals to produce cultivars that do not require sorting after first flowering.

Propagation

In *Piper* species, as in most fruit trees, vegetative propagation is commonly used to ensure genetic identity with the mother plant and to reduce the time to the first harvest.

The most common propagation method is by cuttings (*e.g.*, in *P. nigrum*, *P. cubeba*, *P. longum*, *P. retrofractum*, *P. peepuloides*, *P. betle*, *P. methysticum*, *P. aduncum*, and *P. auritum*) (Utami and Jansen, 1999; Waard and Anunciado, 1999; Denslow and Nelson, 2000; Singh, 2004; Guha, 2006; Thangaselvabal *et al*., 2008; Tynsong *et al*., 2013; Padmanaba, 2016), which are taken from healthy and vigorous plants. If the species is cultivated for peppercorns, it is also important to choose mature stems of the plant. Suckers and stolons should be avoided because, even if they seem to root and grow faster than mature stems, they delay the entry into production by a couple of years (Waard and Anunciado, 1999). For instance, in *P. nigrum* and *P. peepuloides*, pre-topped pieces of terminal orthotropic stems are used (Waard and Anunciado, 1999; Tynsong *et al*., 2013), while in *P. cubeba* cuttings from basal shoots are used (Utami and Jansen, 1999). Cuttings length can vary from 10 cm in *P. nigrum* to 35 cm in *P. betle*, and at least one node is necessary (Waard and Anunciado, 1999; Teo and Banka, 2000; Thangaselvabal *et al*., 2008). In *P. betle*, cuttings have typically 3–5 nodes (Teo and Banka, 2000).

Cuttings can be planted directly in the field or in a nursery. Direct planting requires less management, but nurseries ensure lower mortality rate and faster entry into production (Waard and Anunciado, 1999; Thangaselvabal *et al*., 2008). Indeed, they provide optimal conditions for young cuttings, such as shade, high air humidity, high soil moisture and weed-free soil. In the nursery, cuttings can be planted in common soil, individual pots or polybags. Pots and polybags provide lower root damage at transplantation (Singh, 2004). After a possible period of acclimation, rooted cuttings are transplanted in the field under the chosen support. Usually, cuttings are taken from the mother plants at the beginning of the rainy season, and rooted cuttings are then transplanted during the rainy season (Utami and Jansen, 1999; Waard and Anunciado, 1999; Guha, 2006). This is essential because cuttings need to establish well before the dry season (Singh, 2004). At the beginning, cuttings should be shaded, weeded, mulched and earthed up, but after establishment they do not need any additional care (Utami and Jansen, 1999; Waard and Anunciado, 1999; Tynsong *et al*., 2013). After stem elongation or sprouting, cuttings are pruned back (for instance in *P. nigrum*, *P. longum*, and *P. betle*) and tied to the support (Utami and Jansen, 1999; Waard and Anunciado, 1999; Teo and Banka, 2000; Weiss, 2002).

Propagation is a critical point for *tsiperifery*. Hereafter, we compare the information from other domesticated peppers with the preliminary results from the first *tsiperifery* propagation trials by cuttings (Rafitoharson, 2016). Propagation by cuttings is likely the best option for *tsiperifery*, also considering that vegetative reproduction is its most common reproduction method in the wild. Moreover, in the only germination trial performed until now, *tsiperifery* seeds failed to germinate (Rafitoharson, 2016). Like in other peppers, cuttings should be collected at the beginning of the rainy season. Cuttings of 10–40 cm with 1–5 nodes should be taken from mature parts of healthy and vigorous plants. The protocol from *P. nigrum* and *P. peepuloides* would suggest that the best cuttings could be pre-topped pieces of terminal orthotropic stems. Eventually, the use of plagiotropic reproductive stems for faster entry into production could be tested if they do not present the phenomenon of topophysis. This occurs when cuttings maintain for some time the plagiotropic growth they had as shoots instead of growing immediately erect, and causes a production delay. In a recent trial by Rafitoharson (2016), the performance of two types of cuttings was compared: from creeping stolons and from lateral branches of vegetative orthotropic stems. Creeping stolons showed a better rooting rate than vegetative branches, which mostly failed to root. However, the short duration of the experiment did not allow to check the possibility of topophysis or delayed entry into production, which could be a major drawback for the use of stolons.

Further research is needed to test more types of cuttings, such as those from terminal orthotropic stems and from plagiotropic stems. These trials should last at least two–three years to also account for the effect on entry into production.

Cuttings can be planted directly in the field or, better, in nurseries. Probably, it would be better to plant the cuttings in a common medium since pots or polybags would represent an additional cost for farmers. Soil under *tsiperifery* individuals from the forest containing the potential symbiotic microorganisms can be used as a substrate in order to promote rooting and growth of cuttings (Rafitoharson, 2016). The nursery should be shaded, irrigated and weeded. Rafitoharson (2016) irrigated twice a day and weeded once every two days. After a possible period of acclimation, cuttings should be transplanted into the field during the rainy season under the support. Probably, pruning back after stem elongation or sprouting could promote faster flowering but this should be tested on *tsiperifery* together with the effectiveness of tying the cutting to the support after pruning.

Microclimatic and edaphic conditions

Most *Piper* species are typical rainforest understory species (*e.g.*, *P. nigrum*, *P. cubeba*, *P. longum*, *P. retrofractum*, *P. methysticum*, and *P. sarmentosum*) (Greig, 2004; Jaramillo *et al.*, 2008). They require high average temperature and high annual precipitation rates, which is not usually a problem since they are cultivated at the same latitude of their original habitat. In contrast, the understory microclimatic and edaphic conditions are more difficult to reproduce.

Piper species are shade-loving plants that need constant air humidity, *e.g.*, >80% RH for *P. nigrum* (Thangaselvabal *et al.*, 2008; Lim, 2012b), 40–80% RH for *P. betle* (Guha, 2006), >70% RH for *P. methysticum* (Singh, 2004). They cannot grow or develop physiological disorders if directly exposed to sunlight (*e.g.*, see Thangaselvabal *et al.*, 2008 for *P. nigrum*). Consequently, they are mostly grown under shade trees, with the exception of *P. nigrum* that can ~~eventually~~ be found in unshaded plantations (Waars and Anunciado, 1999; Thangaselvabal *et al.*, 2008).

Most *Piper* species need well-drained humic soil with good water holding capacity (*e.g.*, *P. nigrum*, *P. cubeba*, *P. longum*, *P. betle*, and *P. methysticum*) (Utami and Jansen, 1999; Weiss, 2002; Singh, 2004; Guha, 2006; Thangaselvabal *et al.*, 2008; Nair, 2011). In cultivated systems, this can be attained through litter fall from the living supports, use of mulching and/or other organic fertilizers. Usually, clay soil is preferred (*e.g.*, for *P. cubeba* and *P. betle*) because it retains more organic matter (Weiss, 2002; Guha, 2006).

Given its natural habitat, it would likely be easier to cultivate *tsiperifery* under tree canopy, using the trees themselves as supports. Although no specific information is available, it is probable that also *tsiperifery* requires high soil moisture and high soil organic matter, requirements can be better attained under tree shade. Alike other wild peppers, clay soils are probably better for cultivation, which would benefit from organic fertilization, mulching, and irrigation (where needed).

Supports, shade and cultivation system

As already mentioned, most of the cultivated *Piper* species, and all the species used to produce peppercorns, are climbers. Supports can be artificial or living. Most pepper species are grown on living supports and only few of them (mainly *P. nigrum*) are grown in intensive unshaded plantations on artificial supports. Living supports should be planted at least one year before pepper plants (Waard and Anunciado, 1999), and are regularly pruned, especially before the start of the reproductive season in order to promote flowering (Thangaselvabal *et al.*, 2008).

Cultivation systems can be unshaded or shaded. The unshaded systems are intensive plantations where the pepper plants climb on artificial supports. These systems are restricted to the most intensively cultivated species, especially black pepper. Shaded systems are either plantations or small home gardens. In the first case, pepper plants are planted as intercrop, mostly in areca palm, coffee and cocoa plantations. Pepper plants can grow directly on areca nut and coconut trees or on specific living supports. Alternatively, pepper can be planted in mixed home gardens where it grows on other crop trees. In general, unshaded intensive plantations have higher productivity compared to shaded systems, but they also require more external inputs and management care (irrigation, fertilization, *etc.*) and experience higher phytosanitary risks due to high density (Waard and Anunciado, 1999). Because of higher stress levels and progressive increase in the incidence of pests and diseases, productivity decline happens earlier in unshaded intensive plantations compared to shaded systems leading to shorter replacement times. For example, black pepper lasts 15 years in unshaded systems *vs.* 30 years in shaded systems (Waard and Anunciado, 1999).

Tsiperifery can also be grown on artificial or living supports. Artificial supports are easier to handle but do not provide the required microclimatic and edaphic conditions. In this case, some kind of cover or net should be used to provide constant shade and air humidity. Instead, living supports directly provide the required microclimatic and (partly) edaphic conditions. In the case of plantations, they can also provide additional production, such as fruit, timber and other products. In an agroforestry system on forest edge, the supports would be the forest trees already present in the habitat.

Another potential constraint is that *tsiperifery* may only grow on specific species, the so-called 'associated species'. Further research is needed to clarify this issue and to eventually list these associated species. Some support species found in forests have already been listed (Razafimandimby, 2009; Ratsaraefatrarivo, 2012; Ramahavalisoa, 2017). However, no constant species have been found, since they seem to change upon location. *Tsiperifery* can probably adapt to a very large range of supports, which would be an advantage for cultivation.

For what concerns the cultivation system, three possible solutions can be proposed: (i) unshaded plantation with artificial support and cover; (ii) shaded plantation with living supports; and (iii) agroforestry system on the forest edge, where the naturally present trees are used as supports. In the latter case, only seedlings enrichment is necessary and less management would be required. This system would indirectly benefit the environment by causing local people to adopt agroforestry systems in these habitats as an alternative to current slash-and-burn agricultural systems.

Period to first harvest, full productivity and duration of the productive period

One of the main problems in fruit trees is the long time needed to the first harvest. This is an issue for *Piper* species cultivated for peppercorns (*P. nigrum, P. cubeba*, *P. longum*, *P. retrofractum*, *P. guineense*, and *P. peepuloides*). Careful choice of healthy and mature cuttings and proper nursery care would shorten the time needed for entry into production. Moreover, regular pruning would promote earlier and more abundant flowering and fruiting. Under good management practices, the time to the first yield is typically one year for *P. cubeba* and *P. peepuloides* (Weiss, 2002; Tysong *et al.*, 2013) and 2.5 years for *P. nigrum* (Waard and Anunciado, 1999; Thangaselvabal *et al.*, 2008). Yields are usually low in the first years and gradually increase until entry into full production. For instance, *P. cubeba* reaches full productivity 3–4 years after transplanting (Utami and Jansen, 1999; Weiss, 2002).

The period needed by *tsiperifery* to reach the first harvest and entry into full production is unknown yet, but it would surely take many years since the liana only flowers when it has reached at least 8 m of height. This period could be reduced through proper vegetative propagation and pruning. Similarly, the lifespan of *tsiperifery* is still unknown. Probably, duration of a *tsiperifery* plantation would be stretched to pay-back for the initial investment but the optimal replacement time is yet to be defined.

Two more problematic features of *tsiperifery* are its alternate bearing and the observed heterogeneity of the peppercorn maturity that reduces both fruit quality and production. As in many other fruit tree species, alternate bearing can be managed through balanced fertilization and pruning. Further research on pollination and fecundation should be considered in the short term to improve both peppercorn maturity homogeneity and production. Such knowledge may lead to critical cropping systems adjustments, such as the selection of suitable ecosystems. In the long term, genetic improvement could play a key role to address all the above-mentioned issues.

Control of height, pruning and harvesting method

Another problem common to woody crops, and especially to vines, is plant height control. Short size avoids that plant energies are wasted for vegetative growth instead of being channeled towards production, and facilitates harvesting. This issue is mainly handled by proper pruning. All pepper plants would grow very tall without pruning, thus in cultivated systems they are always maintained under 3 m of height (Nair, 2011). Fruits are always harvested manually, even for *P. nigrum*, sometimes with the help of a tripod ladder (Waard and Anunciado, 1999; Tynsong *et al*., 2013).

Height control is expected to be one of the main problems for *tsiperifery* cultivation since the liana grows up to 15–25 m, which is a major issue for harvesting. Besides regular pruning, in the long term this issue may be addressed through genetic improvement.

Other cultivation practices: irrigation, fertilization, weeding

Most *Piper* species have low input requirements (Utami and Jansen, 1999; Weiss, 2002) and are not usually irrigated (Nair, 2011), with the only exception of *P. betle* (Teo and Banka, 2000). Some species require a high amount of organic fertilizers (*e.g*., *P. betle*) (Teo and Banka, 2000) and all species require some fertilizers and/or mulching (Utami and Jansen, 1999; Waard and Anunciado, 1999; Weiss, 2002; Thangaselvabal *et al*., 2008; Nair, 2011). Weeding also can be important (*e.g*., in *P. nigrum*, *P. retrofractum*, and *P. methysticum*) (Utami and Jansen, 1999; Waard and Anunciado, 1999; Singh, 2004; Thangaselvabal *et al*., 2008). *Piper peepuloides* does not require any care after the third year and it does not need any fertilization, since the prunings from the supports are high enough to provide nutrients (Tynsong *et al*., 2013).

For what concerns *tsiperifery*, some irrigation would be probably needed. Probably, organic fertilizer and mulching would be necessary in plantations, but maybe not in an agroforestry system. Weeding would be necessary, especially for young plants, perhaps also in an agroforestry system.

Plant protection

The major pepper disease is foot-rot, caused by the soil borne fungus *Phytophthora*. This is a major problem in *P. nigrum* (Waard and Anunciado, 1999; Nair, 2011; Ravindran and Kallupurackal, 2012) but it also affects other *Piper* species (Utami and Jansen, 1999; Teo and Banka, 2000). Interestingly, *tsiperifery* is resistant to *Phytophthora* (FAO, 1996) and it has even been proposed as a rootstock for black pepper, although it still needs to be proved that such resistance would be maintained under intensive monocropping systems where plants become more susceptible to pathogens. Due to its potential resistance, *tsiperifery* cultivation could be conducted with no or limited recourse to fungicides, an issue which could open the way to organic or agroecological production, possibly matched by a dedicated certification scheme.

Conclusions

Through this literature review on domesticated *Piper* species, we tried to identify the potential critical issues for the domestication of *tsiperifery* as to suggest preliminary recommendations on how to address them. The most likely critical points are (i) genotype selection; (ii) definition of the standard procedure for vegetative propagation; (iii) reproduction of the microclimatic and edaphic conditions of the rainforest understorey; (iv) choice of the best supports and the cultivation system; (v) reduction of the time needed to entry into production; and (vi) control of plant height. Furthermore, on-field experiments are needed to find suitable management practices, while the study of the domestication process and cultivation techniques of *P. peepuloides* can be used as a model to follow. A complete domestication of *tsiperifery* is not needed, as semi-domestication in an agroforestry system on the forest edge may be sufficient. A participatory approach with strong involvement of local communities is required to ensure best results in terms of both environmental and social sustainability.

Acknowledgments

The authors wish to thank CIRAD Madagascar for providing logistic and technical support to this study and Scuola Superiore Sant'Anna for financially supporting Viviana Ceccarelli's study period in Madagascar.

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Received: Mar. 7, 2019
Accepted: Jan. 20, 2021