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Communication

Sacha Inchi (*Plukenetia volubilis* L.) Is an Underutilized Crop with a Great Potential

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Abstract: *Plukenetia volubilis* (Euphorbiaceae) is an underutilized oilseed crop native to the Amazon basin, where it has been utilized by humans since Incan times. The large seeds contain approximately 45–50% lipid, of which approximately 35.2–50.8% is α-linolenic acid (C18:3 n-3, ω-3) and approximately 33.4–41.0% is linoleic acid (C18:2 n-6, ω-6), the two essential fatty acids required by humans. The seeds also contain 22–30% protein and have antioxidant properties. Due to its excellent nutritional composition and good agronomic properties, it has attracted increasing attention in recent years, and cultivation is expanding. When considering current global challenges, a reformation of our food systems is imperative in order to ensure food security, mitigation of climate change, and alleviation of malnutrition. For this purpose, underutilized crops may be essential tools which can provide agricultural hardiness, a reduced need for external inputs, climate resilience, diet diversification, and improved income opportunities for smallholders. *Plukenetia volubilis* is a promising up and coming crop in this regard and has considerable potential for further domestication; it has an exceptional oil composition, good sensory acceptability, is well suited for cultivation, and has numerous potential applications in, e.g., gastronomy, medicine, and cosmetics.

Keywords: orphan crops; polyunsaturated fatty acids; α-linolenic acid; food security; traditional crops; oilseeds

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1. Introduction to *Plukenetia volubilis*

1.1. Morphology, Phylogeny and Distribution

Plukenetia volubilis is a perennial liana with large, oleaginous seeds. The plants are monecious, the leaves are triangular to ovate with a truncate to cordate base, palmate venation and basilaminar glands, usually with a small knob between them. The racemose inflorescence is axillary or terminal with one to two pistillate flowers situated basally and numerous small, inconspicuous, staminate flowers in condensed cymes situated above. The winged ovary has four carpels, and the style column is elongate and cylindrical, four-lobed at the apex. During fruit maturation, the ovary develops from green and fleshy to brown, woody, and dehiscent. The seeds are lenticular, approximately 1.8 × 0.8 × 1.6 cm in size, and the testa is hard and brown, with dark brown markings (Figure 1). In cultivation, the fruit is often larger and is five- or six-carpellate [1,2]. The genus *Plukenetia* L. (Euphorbiaceae) comprises 25 species, several of which have only recently been described. Circumscription of the genus has undergone several changes during the last four centuries, but the classification was recently revised by Cardinal-McTeague and Gillespie [3]. *Plukenetia* belongs to tribe Plukenetieae, subtribe Plukenetiinae, and is distinguished by four-carpellate ovaries and the presence of two extrafloral nectaries situated basally on the adaxial surface of the leaf blade. The genus is divided into two major clades: the pinnately veined clade, with one primary vein, and the palmately veined clade, including *P. volubilis*, with three to five primary veins [3].

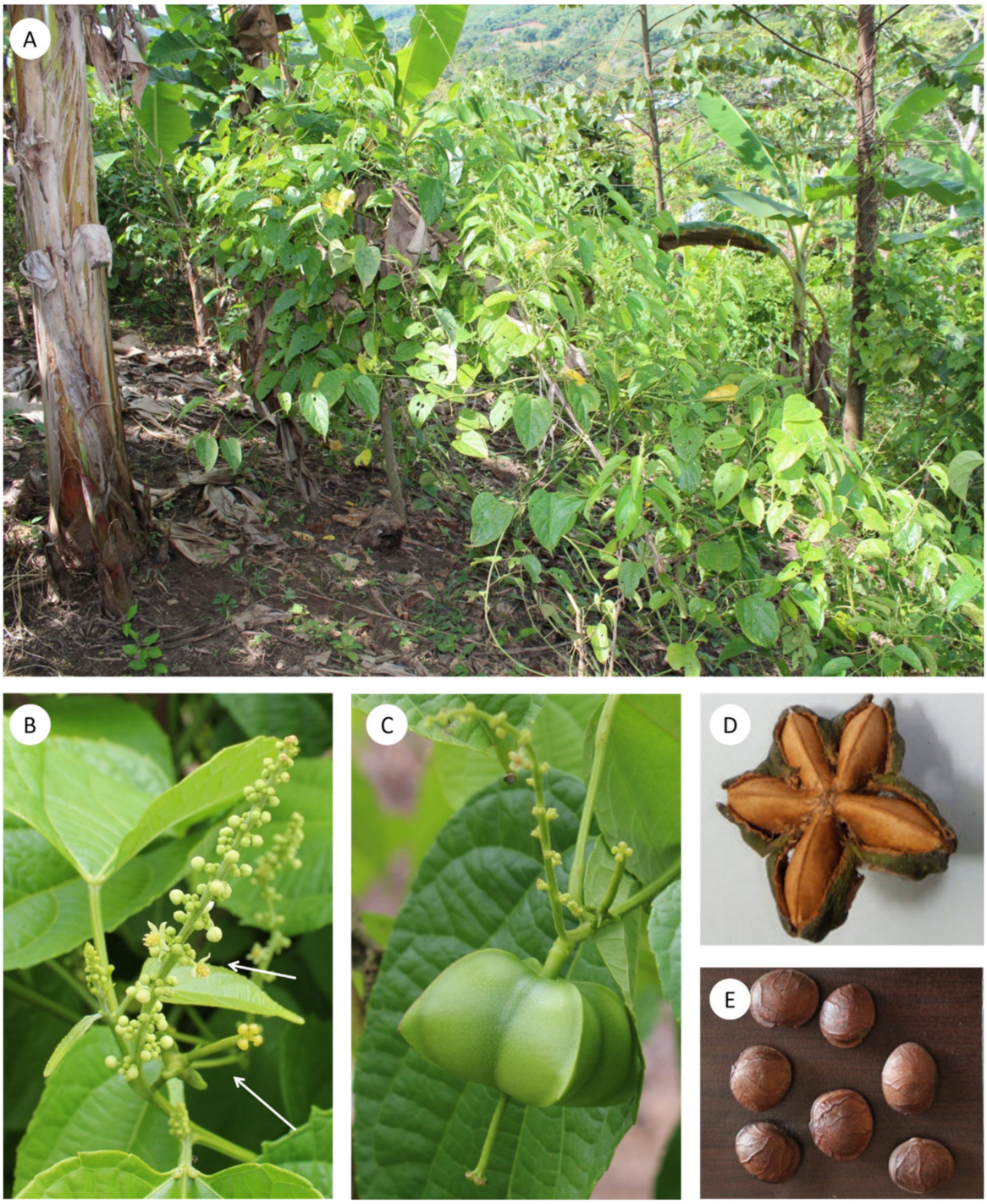

Figure 1. *Plukenetia volubilis*: (**A**) Habitus of plant in polyculture with i.a. banana (*Musa* sp.) and papaya (*Carica papaya* L.) in Iquitos, Peru; (**B**) inflorescence—staminate flowers and a pistillate flower are indicated with arrows; (**C**) inflorescence with developing fruit; (**D**) dry capsule; (**E**) seeds.

Plukenetia volubilis is distributed widely in South America and the Lesser Antilles; it is found in the northern and western parts of the Amazon Basin in Surinam, Venezuela, Colombia, Ecuador, Peru, Bolivia, and Brazil [2]. The most common ecological niche for *P. volubilis* is moist to wet lowland forest, but the species complex also comprises two morphologically differing groups: an open savannah species group and a mid-elevation species group. The open savannah group generally has thicker leaf blades and smaller seeds and fruits, while the mid-elevation group has narrower leaf blades and differing

leaf base morphology compared with typical *P. volubilis*. However, further studies are needed to define species group boundaries better and assess whether the definition of a new, additional species from within the complex is warranted [3].

1.2. Traditional Uses

Plukenetia volubilis has traditionally been consumed in Latin America and has been associated with humans since pre-Hispanic times. Artefacts depicting *P. volubilis* fruits and vines have been found in Incan burial sites along the coast of Peru, indicating that the plant may have been cultivated by the Incans 3000–5000 years ago [4,5].

The vernacular name 'sacha inchi' is Quechuan and is the most commonly used name for *P. volubilis* and other large-seeded species in the genus. However, 'sacha inchik' or 'sacha inchic' is also used depending on the dialect, and the meaning is the same; 'sacha' can be translated to 'mountain' or sometimes to 'false' or 'resembling', and 'inchi' means groundnut/peanut. Less common names for *P. volubilis* include sacha yachi, sacha yuchi, sacha yuchiqui, yuchi, sampannankii, suwaa, correa, amauebe, amui-o, maní de arbol, maní del monte, and maní estrella, several of which hint at the nut-like texture of the seed [5], (D. Cachique. Personal communication, 2016).

Accordingly, some of the most often mentioned culinary uses are similar to the uses of groundnuts; *P. volubilis* seeds are most commonly consumed roasted and salted as a snack, but are also used in confectionery, e.g., dipped in chocolate, or ground to a butter-like substance, milled to flour, or used in a large variety of traditional dishes. These include 'inchi cucho' (a spicy, savory sauce or dip), 'lechona api' (plantain porridge), and 'inchi capi' (chicken or beef soup). Likewise, the young leaves are occasionally eaten in salads or used to brew tea [6,7].

However, while *P. volubilis* has many culinary uses, the most reported use in an ethnobotanical study performed in San Martín, Peru, was for health (67% of answers) [8]. Accordingly, several Peruvian ethnic groups, including the Mayorunas, Chayuhitas, Shipibas, and Boras, have traditionally used a mixture of *P. volubilis* ground seeds and seed oil as a skin cream to rejuvenate and revitalize the skin. Similarly, the Secoyas, Candoshis, Amueshas, and Cashibos, among others, have rubbed *P. volubilis* oil on the skin to relieve muscle pain and rheumatism [7]. The oil and roasted seeds have also been consumed for cholesterol control, cardiovascular health, and gastrointestinal health [8].

With the increasing awareness and popularity of *P. volubilis* in international markets in recent years, several new or differently branded products have also become available, e.g., gourmet oil, protein powder, and encapsulated oil marketed as a dietary supplement. Roasted and salted, or candied, seeds are also marketed.

2. Nutritional Composition

2.1. Oil Composition

Plukenetia volubilis has attracted increasing attention in recent years due to the exceptional nutritional composition of the seeds, in particular the lipid fraction. Approximately 45–50% of the large seeds consist of lipid, although values ranging from 33–58% have been measured; this variation is probably caused by differences in management methods, cultivars, extraction method, or seed processing [9–20].

The lipid fraction is composed of approximately 77.5–84.4% polyunsaturated fatty acids (PUFAs), 8.4–13.2% monounsaturated fatty acids (MUFAs), and 6.8–9.1% saturated fatty acids (SFAs) [11,13,14,21]. Very few vegetable oils have similarly high fractions of PUFAs. However, linseed (*Linum usitatissimum* L.) and chia (*Salvia hispanica* L.) oils are comparable, containing approximately 74 and 80% PUFAs, respectively, while the common cooking oils olive (*Olea europaea* L.) and rapeseed (*Brassica napus* L.) only contain approximately 11 and 27% PUFAs, respectively [22–24].

In *P. volubilis*, the PUFA fraction is composed of the two fatty acids α-linolenic acid (C18:3 n-3, ω-3, ALA) and linoleic acid (C18:2 n-6, ω-6, LA). They are essential fatty acids, i.e., they are required by humans but must be obtained through the diet, as they cannot

be synthesized in the body due to the lack of Δ-12 and Δ-15 desaturases [25,26]. Of the total lipid fraction in *P. volubilis*, 35.2–50.8% is composed of ALA, while 33.4–41.0% is LA. The MUFA fraction includes oleic acid (C18:1 n-9, ω-9, 8.4–10.7% of the total lipid fraction) while the saturated fatty acids include palmitic (C16:0, 4.7–5.7%) and stearic acid (C18:0, 3.0–3.7%) [14,18].

The essential fatty acid LA, an ω-6 fatty acid, has several functions in the human body, including β-oxidation to energy via the Krebs cycle, desaturation and elongation to arachidonic acid and docosapentaenoic acid (DPA), and formation of oxidation products which may lessen the damage caused by oxidative stress in the body [27–30]. Both arachidonic acid and DPA are modified further, e.g., arachidonic acid is the precursor for prostaglandins (pain-response mediation), leukotrienes (inflammatory cytokines), thromboxane (a mediator of cardiovascular disease through blood clot formation), and endocannabinoids (neurotransmitters, modulators of inflammation, gut motility, temperature, appetite, and cardiovascular function) [30–32].

The most abundant fatty acid in *P. volubilis* oil, ALA, is used for energy by undergoing β-oxidation, but is also converted to eicosapentaenoic acid (EPA) which is converted to docosahexaenoic acid (DHA) through the same enzyme cascade as the conversion of LA to DPA [30,31]. EPA and DHA have many effects on human health; perhaps the best documented is the prevention of cardiovascular disease through improvements in i.a. blood pressure, platelet reactivity, thrombosis, cardiac arrhythmia, and the risk of sudden cardiac death, heart rate variability, and inflammation [33–36]. Further, EPA and DHA have a protective effect in mood disorders [37] and can reduce symptoms in patients with depression [38–41]. Brain function is also affected by DHA; low levels of DHA have been found in the brains of persons suffering from Alzheimer's disease. The risk of brain injury can also be decreased, and its treatment benefited, by DHA [30,42,43]. In children, the addition of DHA and arachidonic acid to infant diet formulas improves visual acuity, problem-solving at nine months and cognitive function at 18 months, and, at ages 6–16, dietary intake of n-3 PUFAs correlates positively with cognitive performance [44–47]. Furthermore, the degree of abdominal obesity has been found to correlate negatively with n-3 PUFAs, but positively with n-6 PUFAs [48].

2.2. Seed Proteins

The raw seeds of *P. volubilis* contain approximately 22–30% protein, while the defatted seeds or press cake left after oil extraction contain approximately 53–59% protein, the amount varying with, e.g., cultivar and extraction method [9,13,16,49,50]. The protein is mostly soluble, and the major fractions are albumins, glutelins, globulins, and prolamins [49]. The seeds contain several essential amino acids including leucine, tyrosine, isoleucine, lysine, and tryptophan (approximately 64, 55, 50, 43, and 43 mg g^{-1} of protein, respectively), with a particularly large amount of sulfur-containing amino acids compared with other oilseed crops. Overall, the amino acid composition of the seeds corresponds well to dietary recommendations, and may provide a valuable source of amino acids, particularly in mal- and undernourished population groups [9,49].

2.3. Antioxidants and Other Seed Compounds

The seeds of *P. volubilis* have antioxidant properties, in particular, due to their content of phenols, tocopherols, and carotenoids [14,17,18,51–56].

The measured content of phenolic compounds in the seed oil varies between studies, but Fanali et al. [12] detected 21 phenolic compounds in the oil, and the amount has been shown to increase with the roasting intensity of the seeds [18,56]. Phenols increase the oxidative stability of PUFAs in the oil through their antioxidative properties, and many are known to have a preventive effect on common diseases that may be related to oxidative damage, such as coronary heart disease, stroke, and cancers [57]. Tocopherol content in the seeds of *P. volubilis* is also considerable compared with other commonly consumed nuts and nutlike seeds, e.g., cashews, hazelnuts, and peanuts. Tocopherols are known to be

potent lipophilic antioxidants and are probably associated with the high PUFA content of *P. volubilis* seeds [14]. Further, the seeds of *P. volubilis* contain small amounts of carotenoids, which also possess antioxidant properties, and are of import in nutrition as β-carotene is the precursor for vitamin A (retinol) [58,59].

The total antioxidant capacity of the seed oil pressed from unroasted seeds has been measured to be 18.2 µg Trolox equivalent (TE)/g oil, increasing with roasting to 95.0 µg TE/g for oil from highly roasted seeds [18].

3. Cultivation and Ecology

Plukenetia volubilis is cultivated in approximately 20 different countries, primarily in Latin America, and the largest producer is Peru, with an approximate annual production of 1200 tonnes of seeds (D. Cachique. Personal communication, 19th November 2020). However, production in Peru is rapidly increasing, and new plantations are established each year. In Latin America, *P. volubilis* is further produced in Colombia, Brazil, Ecuador, Bolivia, Nicaragua, Guatemala, Costa Rica, Mexico, and Cuba, and in recent years cultivation has begun in several countries in Asia, particularly in China, but also in Cambodia, Thailand, and Laos (D. Cachique, 19th November 2020, J.E. Engelmann, 13th of November 2020, M. Hermann, 12th November 2020, K.A. Vecht, 28th October 2020, and S. Simonsen, 21st November 2020. Personal communication).

Plukenetia volubilis can grow at temperatures between 10 and 37 °C, although the extremes are not optimal, and temperatures below 8 °C cause severe chilling stress in *P. volubilis* [60,61]. The plants can grow in a variety of soils, but a sandy loam is preferable and good drainage is necessary [60]. Fruit can be produced up to at least 1490 m altitude, but yield declines above 900 m [62]. Total biomass and fruit mass are significantly increased by dry-season irrigation, although seed quality and oil composition are maintained during drought [63,64]. The average yield varies between approximately 150–750 kg ha $^{-1}$ depending on the season and the applied irrigation and fertilization schemes [64].

Plantations are typically established from seeds and anthesis occurs approximately 3–5 months after planting, while fruit maturation occurs after approximately 8–9 months [60,65,66]. Pollination is primarily allogamous, although a small amount of autogamy (approximately 4%) may occur [64,67]. As an alternative to the establishment from seeds, *P. volubilis* can be propagated vegetatively by supplying cuttings with auxin or by grafting to a rootstock. This reduces time to initial flowering and allows for the cultivation of genetically identical plants [68–70].

Because of the climbing growth habit, *P. volubilis* is usually cultivated with support, i.e., stakes or trellises. In Peru, *Erythrina* L. sp. and *Gliricidia* Kunth sp. (Fabaceae) are commonly used as live stakes for *Plukenetia* cultivation, since they have rapid rooting and growth, and increase soil fertility through association with nitrogen-fixing bacteria [71]; this effect can be increased by distributing trimmings from pruning among the plants. Furthermore, live stakes may provide habitats for other organisms, increasing biodiversity compared with cultivation in monoculture.

4. Sustainable Management Practices

Sustainable management practices are becoming increasingly important to ensure food security and reduce environmental impact [72], but no studies focused specifically on sustainable cultivation of *P. volubilis* have been conducted. Nevertheless, some studies of the effect of inoculation with mycorrhiza in *P. volubilis* have been carried out [73,74]. Tian et al. [73] found that inoculation of *P. volubilis* with arbuscular mycorrhiza improved growth both under drought and well-watered conditions; specific leaf area, photosynthetic rate, and root volume was increased. Drought tolerance was hypothesized to be improved considerably by increased production of antioxidative enzymes, including guaiacol peroxidase and catalase, leading to a reduction in oxidative damage. Inoculation with *G. versiforme* had a better effect than inoculation with *P. occultum*, however, inoculation with both symbionts had the largest effect [73]. In agreement with the results of Tian et al. [73],

Caro et al. [74] observed that the number of male and female flowers on *P. volubilis* was significantly increased, and there was a tendency for increased fruit set when plants were inoculated with *Glomus* sp. Concurrently, both studies concluded that mycorrhiza has considerable potential in improving the cultivation of *P. volubilis*, especially in arid or semi-arid regions [73,74].

To our knowledge, no studies of poly-cropping systems including *P. volubilis* exist, but the plant has traditionally been cultivated with subsistence crops as well as fruit trees, timber trees, or cover crops [75] (N. Paredes. Personal communication, 2016), and is still commonly cultivated in composite systems, e.g., in home gardens or loosely scattered among other cash crops (personal observations, 2015–2018). Proyecto Perúbiodiverso [75] and Loaiza [71] emphasize increased soil fertility and reduced erosion, reduction of pest problems, and increase of water availability as advantages of cultivating *P. volubilis* with other crops. According to Proyecto Perúbiodiverso [75], these advantages may be gained by the cultivation of *P. volubilis* with subsistence crops, such as beans (especially *Phaseolus* L. spp.), groundnuts (*Arachis hypogaea* L.), manioc (*Manihot esculenta* Crantz.), maize (*Zea mays* L.), and banana (*Musa* L. spp.), with timber trees (e.g., *Guazuma ulmifolia* Lam., *Swietenia macrophylla* King, *Cedrela odorata* L., *Cedrelinga cateniformis* (Ducke) Ducke, *Simarouba amara* Aubl., *Schizolobium amazonicum* Ducke), or with fruit trees. These suggestions agree with those of Manco [66]. Loaiza [71] also mentions that *P. volubilis* can be cultivated in agroforestry or intercropping systems.

5. Limitations and Breeding Opportunities

Plukenetia volubilis is a highly promising crop, primarily due to the nutritional composition of the seeds; however, further study of the plant and development of breeding strategies will likely prove beneficial. Importantly, although there is focus on sustainability in the plants' native range, exploration of more sustainable management practices will be advantageous, with regards to both biodiversity and climate, and might also improve product quality and provide opportunities for product branding and marketing. Additionally, although the seed oil has been approved for consumption in the European Union, the seeds of *P. volubilis* are not yet approved due to a lack of knowledge concerning the alkaloid content and composition in the seeds [76]. Studies indicate that the amount of alkaloid compounds in the seeds is significantly reduced by thermal processing [77]. However, the recent decision from the European Food Safety Authority [76] nevertheless underlines the need for further documentation of the safety of consumption of the seeds, including details on potentially allergenic or toxic compounds.

Furthermore, very little breeding of *P. volubilis* has been carried out, and the plant is still not considered fully domesticated [78]. However, breeding might not only provide agronomical advantages but might also provide higher yield or improved sensory qualities. Similarly, further exploration of the domestication potential of other large-seeded species in the genus would be fascinating, both as crops in their own right, but possibly also as material for the development of hybrids with *P. volubilis*.

6. Future Potential

Current global challenges include climate change, degradation of land and environment, population growth, and lack of food security. Accordingly, our food systems need to be optimized to ensure food security while avoiding global ecosystem collapse and the subsequent loss of ecosystem services. It is becoming ever more apparent that upscaling of current agricultural systems, in particular monocultures, is not sufficient for this purpose, and alternative strategies are needed [79–81]. Neglected and underutilized crops may prove necessary resources for the reformation of our food production systems by improving, e.g., climate change resilience, genetic diversity, and the nutritional value of agricultural products.

Plukenetia volubilis has considerable potential for contributing to these goals, as the plants can thrive in a broad range of environmental conditions, have an exceptional

nutritional composition, and may be an economically beneficial alternative crop for small-scale farmers. Further, a wide variety of cultivars and a high genetic diversity of germplasm is available, providing outstanding opportunities for further domestication and breeding, aiding in efficient integration of *P. volubilis* in sustainable cultivation systems. On a local scale, *P. volubilis* may, therefore, aid in food security and alleviation of malnutrition, as well as provide economic benefits, while on a broader scale it may contribute to the solution to our global challenges.

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