 doi:10.20944/preprints202105.0090.v1

Communication

Sacha inchi (*Plukenetia volubilis* L.) – an underutilized crop with a great potential

Nete Kodahl and Marten Sørensen

Department of Plant and Environmental Sciences, University of Copenhagen, Thorvaldsensvej 40, DK-1871 Frederiksberg C, Denmark

Abstract

Plukenetia volubilis is an underutilized oilseed crop native to the Amazon basin, where it has been utilised by humans since Incan times. The large seeds contain approx. 45–50 % lipid, of which approx. 35.2–50.8 % is α-linolenic acid (C18:3 n-3, ω-3) and approx. 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 and 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

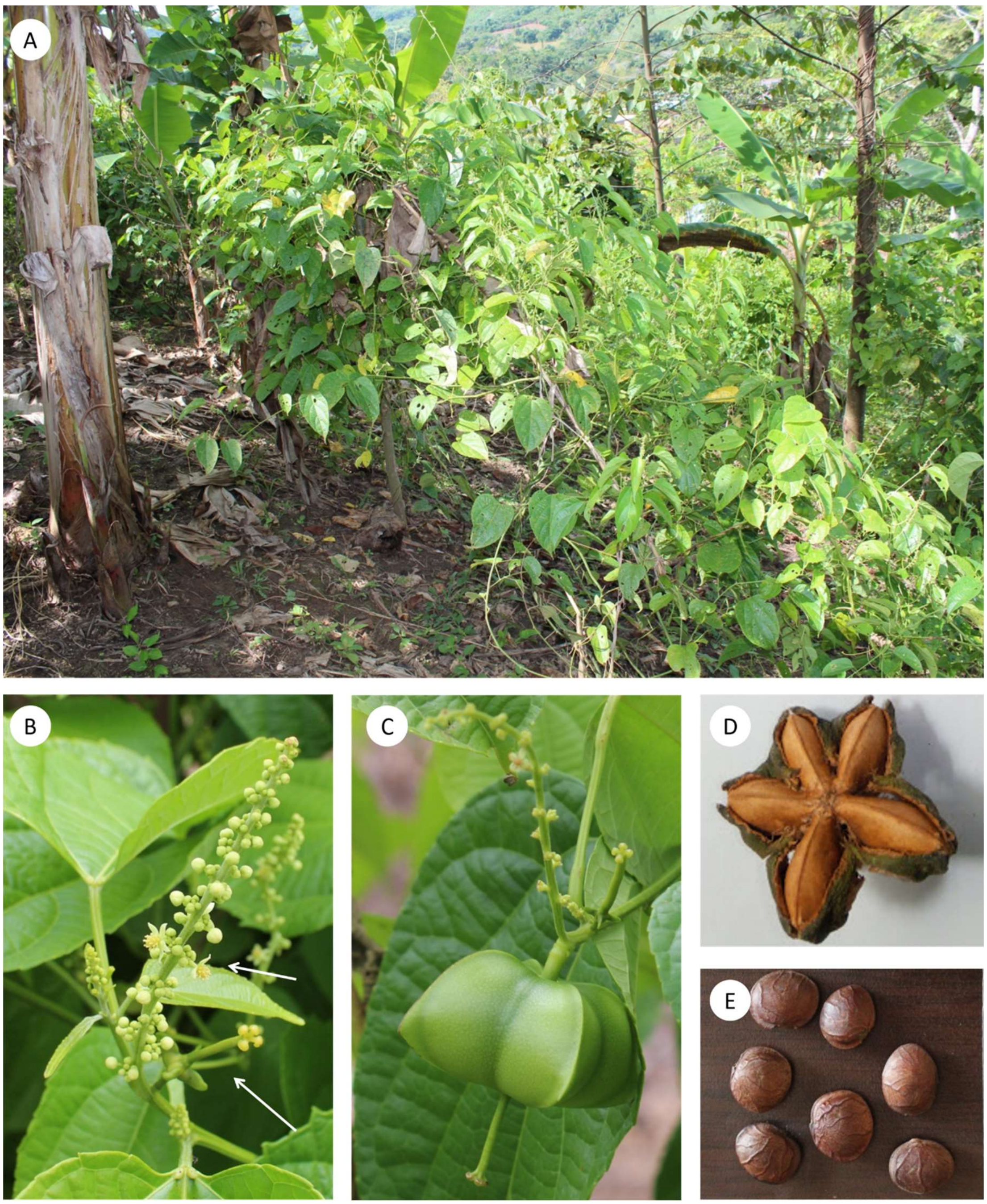
Orphan crops, polyunsaturated fatty acids, α-linolenic acid, food security, traditional crops, oilseeds

1. Introduction to *P. volubilis*

1.1. Morphology 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 1–2 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, approx. 1.8 × 0.8 × 1.6 cm in size and the testa is hard and brown, with dark brown markings (Fig. 1). In cultivation, the fruit is often larger and is 5- or 6-carpellate [1,2].

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 to 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].



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 May 2021 doi:10.20944/preprints202105.0090.v1

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

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 already 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 nutlike texture of the seed [5], (D. Cachique pers. comm. 2016).

Accordingly, some of the most often mentioned culinary uses are similar to the uses of groundnuts; most commonly *P. volubilis* seeds are 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, savoury sauce or dip), 'lechona api' (plantain porridge), and 'inchi capi' (chicken or beef soup). Likewise, occasionally the young leaves are eaten in salads or used to brew tea [6,7].

However, while *P. volubilis* has many culinary uses, the most mentioned 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 *P. volubilis* mixture of 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. However, 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. Approx. 45–50 % of the large seeds consist of lipid, although values ranging from 33–58 % have been measured; the

 doi:10.20944/preprints202105.0090.v1

variation is probably caused by differences in management methods, cultivars, extraction method, or seed processing [9–20].

The lipid fraction is composed of approx. 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, approx. 74 and 80 % PUFAs, respectively, while the common cooking oils olive (*Olea europaea* L.) and rapeseed (*Brassica napus* L.) only contain approx. 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 [27,28,29,30]. Both arachidonic acid and DPA are modified further, e.g. arachidonic acid is the precursor for, i.e. prostaglandins (pain response mediation), leukotrienes (inflammatory cytokines), thromboxane (mediators 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 and carbon 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 has been found in the brains of persons suffering from Alzheimer's disease, and it has been demonstrated that the risk of brain injury can 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 contains approx. 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 (approx. 64, 55, 50, 43, and 43 mg/g of protein, respectively), with a particularly large amount of sulphur-containing amino acids compared to 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, e.g. [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 to 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 approx. 20 different countries, primarily in Latin America, and the largest producer is Peru, with an approximate annual production of 1200 tonnes of seeds (pers. comm. D. Cachique). 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 several places in Asia, particularly in China, but also in Cambodia, Thailand, and Laos (pers. comm. D. Cachique, J.E. Engelmann, M. Hermann, K.A. Vecht, and S. Simonsen).

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]. 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].

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 (approx. 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]; an effect which can be increased by distributing trimmings from pruning among the plants. Furthermore, live stakes may provide habitats for other organisms, increasing biodiversity compared to 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 incremented 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 conclude that mycorrhiza has considerable potential in improving the cultivation of *P. volubilis*, especially in arid or semi-arid regions [73,74].

Apparently, 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] (pers. comm. N. Paredes 2016) and is still commonly cultivated in composite systems, e.g. in home gardens or loosely scattered among other cash crops (pers. obs. 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], and Loaiza [71] also mention that *P. volubilis* can be cultivated in agroforestry or intercropping systems.

 doi:10.20944/preprints202105.0090.v1

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 probably prove beneficial. Importantly, although there is focus on sustainability in the plants' native range, exploration of more sustainable management practices will be advantageous, both with regards to biodiversity and climate, but might also improve product quality and provide opportunities for product branding and marketing. Also, even though 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 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, alleviation of malnutrition, as well as provide economic benefits, while on a broad scale it may be part of the solution to our global challenges.

Funding
This work was supported by Svend G. Fiedler and Spouse's stipend, Torben and Alice Frimodt's scholarship and the Oticon foundation.

Acknowledgements
We are very grateful to Danter H. Cachique, Jaime E. Engelmann, Michael Hermann, Karen A. Vecht, and Steen Simonsen for kind assistance and fruitful discussions.

Author contributions
The authors have contributed equally to the work.

References
1. Gillespie, L.J. A Synopsis of Neotropical *Plukenetia* (Euphorbiaceae) Including Two New Species. *Syst. Bot.* **1993**, *18(4)*, 575–592.
2. Gillespie, L.J.; Armbruster, W.S. A Contribution to the Guianan Flora: *Dalechampia, Haematostemon, Omphalea, Pera, Plukenetia,* and *Tragia* (Euphorbiaceae) with Notes on Subfamily Acolyphoideae. *Smithson. Contrib. Bot.* **1997**, *86*, 1–48.
3. Cardinal-McTeague, W.M.; Gillespie, L.J. A Revised Sectional Classification of *Plukenetia* L. (Euphorbiaceae, Acalyphoideae) with Four New Species from South America. *Syst. Bot.* **2020**, *45(3)*, 507–536.
4. Bernal, H.Y.; Correa Q., J.E. Plukenetia volubilis. In *Especies vegetales promisorias de los países del Convenio Andrés Bello*; Bernal, H.Y., Correa Q., J.E. Eds.; Secretaría Ejecutiva del Convenio Andrés Bello, Bogotá, Colombia, 1992; Volumen 7, pp. 577–596.
5. Brack Egg, A. *Diccionario Enciclopedico de Plantas Utiles del Peru*. PNUD, Cuzco, Perú, 1999; 400 p.
6. Flores, D. 2010. *Uso Histórico: Sacha Inchi* Plukenetia volúbilis *L*. Proyecto Perubiodiverso, Peru, 27 p. Available online: https://repositorio.promperu.gob.pe/bitstream/handle/123456789/1371/Uso_historico_sacha_inchi_2010_keyword_principal.pdf?sequence=1&isAllowed=y (accessed on 18 January 2021).
7. Flores, D.; Lock, O. Revalorizando el uso milenario del sacha inchi (*Plukenetia volubilis* L.) para la nutrición, la salud y la cosmética. *Rev. de Fitoter.* **2013**, *13(1)*, 23–30.
8. del Castillo, A.M.R.; Gonzalez-Aspajo, G.; Sánchez-Márquez, M.F.; Kodahl, N. Ethnobotanical Knowledge in the Peruvian Amazon of the Neglected and Underutilized Crop Sacha Inchi (*Plukenetia volubilis* L.). *Econ. Bot.* **2019**, *73(2)*, 281–287.
9. Hamaker, B.R.; Valles, C.; Gilman, R.; Hardmeier, R.M.; Clark, D.; Garcia, H.H.; Gonzales, A.E.; Kohlstad, I.; Castro, M.; Valdivia, R.; Rodriguez, T.; Lescano, M. Amino Acid and Fatty Acid Profiles of the Inca Peanut (*Plukenetia volubilis*). *Cereal Chem.* **1992**, *69(4)*, 461–463.
10. Guillén, M.D.; Ruiz, A.; Cabo, N.; Chirinos, R.; Pascual, G. Characterization of Sacha Inchi (*Plukenetia volubilis* L.) Oil by FTIR Spectroscopy and 1H NMR. Comparison with Linseed Oil. *JAOCS* **2003**, *80(8)*, 755–762.
11. Follegatti-Romero, L.A.; Piantino, C.A.; Grimaldi, R.; Fernando, A.C. Supercritical CO_2 extraction of omega-3 rich oil from Sacha inchi (*Plukenetia volubilis* L.) seeds. *J Supercrit Fluids* **2009,** *49*, 323–329.
12. Fanali, C.; Dugo, L.; Cacciola, F.; Beccaria, M.; Grasso, S.; Dachà, M.; Dugo, P.; Mondello, L. Chemical Characterization of Sacha Inchi (*Plukenetia volubilis* L.) Oil. *J. Agric. Food Chem* **2011***, 59*, 13043–13049.

13. Gutiérrez, L.-P.; Rosada, L.-M.; Jiménez, A. Chemical composition of Sacha Inchi (*Plukenetia volubilis* L.) seeds and characteristics of their lipid fraction. *GRASAS ACEITES* **2011**, *62(1)*, 76–83.
14. Chirinos, R.; Zuloeta, G.; Pedreschi, R.; Mignolet, E.; Larondelle, Y.; Campos, D. Sacha inchi (*Plukenetia volubilis*): A seed source of polyunsaturated fatty acids, tocopherols, phytosterols, phenolic compounds and antioxidant capacity. *Food Chem.* **2013**, *141*, 1732–1739.
15. Souza, A.H.P.; Gohara, A.K.; Rodrigues, A.C.; Souza, N.E.; Visentainer, J.V.; Matsushita, M. Sacha inchi as potential source of essential fatty acids and tocopherols: multivariate study of nut and shell. *Acta Sci. Technol.* **2013**, *35(4)*, 757–763.
16. Ruiz, C.; Diaz, C.; Anaya, J.; Rojas, R. Análisis proximal, antinutrientes, perfil de ácidos grasos y de aminoácidos de semillas y tortas de 2 especies de sacha inchi (*Plukenetia volubilis* y *Plukenetia huayllabambana*). *Rev. Soc. Quím. Perú*. **2013**, *79(1)*, 29–36.
17. Takeyama, E., Fukushima, M. Physicochemical Properties of *Plukenetia volubilis* L. Seeds and Oxidative Stability of Cold-pressed Oil (Green Nut Oil). *Food Sci. Technol. Res.* **2013**, *19(5)*, 875–882.
18. Cisneros, F.H.; Paredes, D.; Arana, A.; Cisneros-Zevallos, L. Chemical Composition, Oxidative Stability and Antioxidant Capacity of Oil Extracted from Roasted Seeds of Sacha-Inchi (*Plukenetia volubilis* L.). *J. Agric. Food Chem.* **2014**, *62*, 5191–5197.
19. Zanqui, A.B.; Silva, C.M.; Morais, D.R.; Santos, J.M.; Ribeiro, S.A.O.; Eberlin, M.N.; Cardozo-Filho, L.; Visentainer, J.V.; Gomes, S.T.M.; Matsushita, M. Sacha inchi (*Plukenetia volubilis* L.) oil composition varies with changes in temperature and pressure in subcritical extraction with *n*-propane. *Ind. Crops Prod.* **2016**, *87*, 64–70.
20. Triana-Maldonado, D.M.; Torijano-Gutiérrez, S.A.; Giraldo-Estrada, C. Supercritical CO2 extraction of oil and omega-3 concentrate from Sacha inchi (*Plukenetia volubilis* L.) from Antioquia, Colombia. *Grasas y Aceites* **2017**, *68(1)*.
21. Maurer, N.E.; Hatta-Sakoda, B.; Pascual-Chagman, G.; Rodriguez-Saona, L.E. Characterization and authentication of a novel vegetable source of omega-3 fatty acids, sacha inchi (*Plukenetia volubilis* L.) oil. *Food Chem.* **2012**, *134*, 1173–1180.
22. Ciftci, O.N.; Przybylski, R.; Rudzinska M. Lipid components of flax, perilla, and chia seeds. *Eur. J. Lipid Sci. Technol.* **2012**, *114*, 794–800.
23. USDA (2020a) Rapeseed oil. US Department of Agriculture FoodDataCentral. Available online: https://fdc.nal.usda.gov/fdc-app.html#/food-details/789038/nutrients (accessed on 25 October 2020).
24. USDA (2020b) Olive oil. US Department of Agriculture FoodDataCentral. Available online: https://fdc.nal.usda.gov/fdc-app.html#/food-details/789040/nutrients (accessed on 25 October 2020).
25. Burr, G.O.; Burr, M.M. On the nature and role of the fatty acids essential in nutrition. *J. Biol. Chem.* **1930**, *82*, 345–367.
26. Sinclair, A.J.; Attar-Bashi, N.M.; Li, D. What Is the Role of α-Linolenic Acid for Mammals? *Lipids* **2002**, *37(12)*, 1113–1123.
27. Novak, E.M.; Dyer, R.A.; Innis, S.M. High dietary ω-6 fatty acids contribute to reduced docosahexaenoic acid in the developing brain and inhibit secondary neurite growth. *Brain Res.* **2008**, *1237*, 136–145.
28. Wang, R.; Kern, J.T.; Goodfriend, T.L.; Ball, D.L.; Luesch, H. Activation of the antioxidant response by specific oxidized metabolites of linoleic acid. *Prostaglandins Leukot. Essent. Fatty Acids* **2009**, *81(1)*, 53–59.
29. Ramsden, C.E.; Ringel, A.; Feldstein, A.E.; Taha, A.Y.; MacIntosh, B.A.; Hibbeln, J.R.; Majchrzak-Hong, S.F.; Faurot, K.R.; Rapoport, S.I.; Cheon, Y.; Chung, Y.-M.;

 doi:10.20944/preprints202105.0090.v1

Berk, M.; Mann, J.D. Lowering dietary linoleic acid reduces bioactive oxidized linoleic acid metabolites in humans. *Prostaglandins Leukot. Essent. Fatty Acids* **2012**, *87*, 135–141.

30. Glick, N.R.; Fischer, M.H. The Role of Essential Fatty Acids in Human Health. *Evid.-Based Complementary Altern. Med.* **2013***, 18(4)*, 268–289.
31. Lauritzen, L.; Hansen, H.S.; Jørgensen, M.H.; Michaelsen, K.F. The essentiality of long chain n-3 fatty acids in relation to development and function of the brain and retina. *Prog. Lipid Res.* **2001**, *40*, 1–94.
32. Pacher, P.; Mukhopadhyay, P.; Mohanraj, R.; Godlewski, G.; Bátkai, S.; Kunos, G. Modulation of the Endocannabinoid System in Cardiovascular Disease – Therapeutic Potential and Limitations. *Hypertension* **2008**, *52*, 601–607.
33. Caterina, R. n-3 Fatty Acids in Cardiovascular Disease. *N. Engl. J. Med.* **2011**, *364*, 2439–2450.
34. Mozaffarian, D.; Wu, J.H.Y. Omega-3 Fatty Acids and Cardiovascular Disease - Effects on Risk Factors, Molecular Pathways, and Clinical Events. *J. Am. Coll. Cardiol.* **2011**, *58(20)*, 2047–2067.
35. Calder, P.C. Mechanisms of Action of (n-3) Fatty Acids. *J. Nutr.*, Supplement: Heart Healthy Omega-3s for Food—Stearidonic Acid (SDA) as a Sustainable Choice **2012**, doi:10.3945/jn.111.155259.
36. Jump, D.B.; Depner, C.M.; Tripathy, S. Omega-3 fatty acid supplementation and cardiovascular disease. *J. Lipid Res.* **2012**, *53*, 2525–2545.
37. Freeman, M.P.; Hibbeln, J.R.; Wisner, K.L.; Davis, J.M.; Mischoulon, D.; Peet, M.; Keck, P.E.; Marangell, L.B.; Richardson, A.J.; Lake, J.; Stoll, A.L. Omega-3 Fatty Acids: Evidence Basis for Treatment and Future Research in Psychiatry. *J. Clin. Psychiatry* **2006**, *67*, 1954–1967.
38. Lin, P.-Y.; Su, K.-P. A meta-analytic review of double-blind, placebo-controlled trials of antidepressant efficacy of omega-3 fatty acids. *J. Clin. Psychiatry* **2007**, *68(7)*, 1056–1061.
39. Ross, B.M.; Seguin, J.; Sieswerda, L.E. Omega-3 fatty acids as treatments for mental illness: which disorder and which fatty acid? *Lipids Health Dis.* **2007**, *6(21)*, doi:10.1186/1476-511X-6-21.
40. Hallahan, B.; Ryan, T.; Hibbeln, J.R. et al. Efficacy of omega-3 highly unsaturated fatty acids in the treatment of depression. *Br. J. Psychiatry*. **2016**, doi:10.7326/ACPJC-2016-165-6-029.
41. Sarris, J.; Murphy, J.; Mischoulon, D. et al. Adjunctive nutraceuticals for depression: a systematic review and meta-analyses. *Am. J. Psychiatry* **2016**, *173*, 575–87.
42. Lewis, M.D.; Bailes, J. Neuroprotection for the Warrior: Dietary Supplementation With Omega-3 Fatty Acids. *Mil. Med.* **2011**, *176(10)*, 1120–1127.
43. Wu, A.; Ying, Z.; Gomez-Pinilla, F. The Salutary Effects of DHA Dietary Supplementation on Cognition, Neuroplasticity, and Membrane Homeostasis after Brain Trauma. *J. Neurotrauma* **2011**, *28*, 2113–2122.
44. Drover, J.; Birch, E.E.; Hoffman, D.R.; Castañeda, Y.S.; Morale, S.E. Three Randomized Controlled Trials of Early Long-Chain Polyunsaturated Fatty Acid Supplementation on Means-End Problem Solving in 9-Month-Olds. *Child Dev.* **2009**, *80(5)*, 1376–1384.
45. Birch, E.E.; Carlson, S.E.; Hoffman, D.R. et al. The DIAMOND (DHA Intake and measurement of neural development) Study: a double-masked, randomized controlled clinical trial of the maturation of infant visual acuity as a function of the dietary level of docosahexaenoic acid. *Am. J. Clin. Nutr*. **2010**, *91*, 848–859.
46. Drover, J.R.; Hoffman, D.R.; Castañeda, Y.S.; Morale, S.E.; Garfield, S.; Wheaton, D.H.; Birch, E.E. Cognitive function in 18-month-old term infants of the DIAMOND

study: A randomized, controlled clinical trial with multiple dietary levels of docosahexaenoic acid. *Early Hum. Dev.* **2010**, *87*, 223–230.
47. Lassek, W.D.; Gaulin, S.J.C. Sex differences in the relationship of dietary fatty acids to cognitive measures in American children. *Frontiers in Evolutionary Neuroscience* **2011**, *3(5)*, 1–8.
48. Garaulet, M.; Pérez-Llamas, F.; Pérez-Ayala, M.; Martínez, P.; Medina, F.S.; Tebar, F.J.; Zamora, S. Site-specific differences in the fatty acid composition of abdominal adipose tissue in an obese population from a Mediterranean area: relation with dietary fatty acids, plasma lipid profile, serum insulin, and central obesity. *Am. J. Clin. Nutr.* **2001**, *74*, 585–591.
49. Sathe, S.K.; Kshirsagar, H.H.; Sharma, G.M. Solubilization, Fractionation, and Electrophoretic Characterization of Inca Peanut (*Plukenetia volubilis* L.) Proteins. *Plant. Foods. Hum. Nutr.* **2012**, *67*, 247–255.
50. Chirinos, R.; Aquino, M.; Pedreschi, R.; Campos, D. Optimized methodology for alkaline and enzyme-assisted extraction of protein from sacha inchi (*Plukenetia volubilis*) kernel cake. *J. Food Process Eng.* **2016**, *40(2)*, doi:10.1111/jfpe.12412.
51. Jáuregui, A.M.; Escudero, F.R.; Ortiz-Ureta, C.A.; Castañeda, B.C.; Mendoza, E.B.; Farfán, J.Y.; Asencios, D.C. Evaluación del contenido de fitoesteroles, compuestos fenólicos y métodos químicos para determiner la actividad antioxidante en semilla de sacha inchi (*Plukenetia volubilis* L.). *Rev. Soc. Quím. Perú* **2010**, *76(3)*, 234–241.
52. Saavedra, E.F.C.; Viera, S.F.C.; Alfaro, C.E.R. Estudio fitoquímico de *Plukenetia volubilis* L. y su efecto antioxidante en la lipoperoxidación inducida por Fe^{3+} /ascorbato en hígado de *Rattus rattus* var. *albinus*. *UCV – Scientia* **2010**, *2(1)*, 11–21.
53. Nascimento, A.K.L.; Melo-Silveira, R.F.; Dantas-Santos, N.; Fernandes, J.M.; Zucolotto, S.M.; Rocha, H.A.O.; Scortecci, K.C. Antioxidant and Antiproliferative Activities of Leaf Extracts from *Plukenetia volubilis* Linneo (Euphorbiaceae). *J Evid. Based Complementary Altern. Med.* **2013**, doi:10.1155/2013/950272.
54. Liu, Q.; Xu, Y.K.; Zhang, P.; Na, Z.; Tang, T.; Shi, Y.X. Chemical composition and oxidative evolution of Sacha Inchi (*Plukentia volubilis* L.) oil from Xishuangbanna (China). *Grasas y Aceites* **2014**, *65(1)*, doi:10.3989/gya.075713.
55. Franco-Quino, C.; Muñoz-Espinoza, D.; Gómez-Herreros, C. et al. Caracteristicas fitoquímicas y capacidad antioxidante in vitro de *Aloe vera, Plukenetia volubilis, Caiophora carduifolia, Cecropia membranácea*. *An. Fac. Med.* **2016**, *77(1)*, 9–13.
56. Sterbova, L.; Cepkova, P.H.; Viehmannova, I.; Cachique, D.H. Effect of thermal processing on phenolic content, tocopherols and antioxidant activity of sacha inchi kernels. *J. Food Process. Preserv.* **2016**, *41(2)*, doi:10.1111/jfpp.12848.
57. Bendini, A.; Cerretani, L.; Carrasco-Pancorbo, A.; Gómez-Caravaca, A.M.; Segura-Carretero, A.; Fernández-Gutiérrez, A.; Lercker, G. Phenolic Molecules in Virgin Olive Oils: a Survey of Their Sensory Properties, Health Effects, Antioxidant Activity and Analytical Methods. An Overview of the Last Decade. *Molecules* **2007**, *12*, 1679–1719.
58. Palozza, P.; Krinsky, N.I. Antioxidant effects of carotenoids in Vivo and in Vitro: An overview. *Meth. Enzymol.* **1992**, *213*, 403–420.
59. Shahidi, F., Shukla, V.K.S. Nontriacylglycerol constituents of fats, oils. *INFORM* **1996**, *7(11)*, 1227–1232.
60. Arévalo, G.G. *El cultivo del Sacha Inchi (Plukenetia volubilis L.) en la Amazonía*. Programa Nacional de Investigación en Recursos Genéticos y Biotecnología (PRONARGEB), Tarapoto, Perú, 1995.
61. Lei, Y.-B.; Zheng, Y.-L.; Dai, K.-J.; Duan, B.-L.; Cai, Z.-Q. Different responses of photosystem I and photosystem II in three tropical oilseed crops exposed to chilling stress and subsequent recovery. *Trees* **2014**, *28*, 923–933.

62. Cai, Z.Q.; Jiao, D.Y.; Tang, S.X.; Dao, X.S.; Lei, Y.B.; Cai C.T. Leaf Photosynthesis, Growth, and Seed Chemicals of Sacha Inchi Plants Cultivated Along an Altitude Gradient. *Crop Sci.* **2012**, *52*, 1859–1867.
63. Jiao, D.Y.; Xiang, M.H.; Li, W.G.; Cai, Z.-Q. Dry-season irrigation and fertilisation affect the growth, reproduction, and seed traits of *Plukenetia volubilis* L. plants in a tropical region, *J. Hortic. Sci.* **2012**, *87(4)*, 311–316, doi:10.1080/14620316.2012.11512870
64. Gong, H.D.; Geng, Y.J.; Yang, C.; Jiao, D.Y.; Chen, L.; Cai, Z.-Q. Yield and resource use efficiency of *Plukenetia volubilis* plants at two distinct growth stages as affected by irrigation and fertilization. *Sci. Rep.* **2018**, *8*, 80, doi:10.1038/s41598-017-18342-6
65. Cachique, D.H. *Biología Floral y Reproductiva de Plukenetia volubilis L. (Euphorbiaceae) – (Sacha Inchi)*. Universidad Nacional de San Martín, Tarapoto, Perú, 2006.
66. Manco, E.I.C. *Cultivo de sacha inchi.* Instituto Nacional de Investigación y Extensión Agraria, Tarapoto, Perú, 2006.
67. Valente, M.S.F.; Lopes, M.T.G.; Chaves, F.C.M.; Pantoja, M.C.; Sousa, F.M.G.; Chagas, E.A. Molecular genetic diversity and mating system in sacha inchi progenies. *Pesq. Agropec. Trop.* **2017**, *47(4)*, 480–487.
68. Cachique, D.; Rodriguez, Á.; Ruiz-Solsol, H.; Vallejos, G.; Solis, R. Propagacion vegetativa del sacha inchi (*Plukenetia volubilis* L.) mediante enraizamiento de estacas juveniles en cámaras de subirrigación en la Amazonia Peruana. *Folia Amazón.* **2011**, *20(1–2)*, 95–100.
69. Rodrigues, P.H.V.; Bordignon, S.R.; Ambrosano, G.M.B. Desempenho horticultural de plantas propagadas *in vitro* de *Sacha inchi*. *Ciênc. Rural* **2014**, *44(6)*, 1050–1053.
70. Cachique, D.H.; Solsol, H.R.; Sanchez, M.A.G.; López, L.A.A.; Kodahl, N. Vegetative propagation of the underutilized oilseed crop sacha inchi (*Plukenetia volubilis* L.). *Genet. Resour. Crop Evol.* **2018**, *65*, 2027–2036.
71. Loaiza, M.E.E. *Manejo Agroecologico del Cultivo de Sacha Inchi (*Plukenetia volubilis *L.)*. Universidad Agraria del Ecuador, Guayaquil, Ecuador, 2013.
72. Funabashi, M. Synecological farming: Theoretical foundation on biodiversity responses of plant communities. *Plant Biotechnol. J.* **2016**, *33*, 213–234.
73. Tian, Y.H.; Lei, Y.B.; Zheng, Y.L.; Cai, Z.-Q. Synergistic effect of colonization with arbuscular mycorrhizal fungi improves growth and drought tolerance of *Plukenetia volubilis* seedlings. *Acta Physiol. Plant.* **2013**, *35*, 687–696.
74. Caro, L.A.P.; Zumaqué, L.E.O.; Violeth, J.L.B. Efecto de la micorrización y el lombriabono sobre el crecimiento y desarrollo del Sacha inchi *Plukenetia volubilis* L. *Temas Agrarios* **2017**, *23(1)*, 18–28.
75. Proyecto Perúbiodiverso. *Manual de producción de sacha inchi para el biocomercio y la agroforestería sostenible.* Lima, Perú, 2009.
76. European Food Safety Authority. Technical Report on the notification of roasted seeds from *Plukenetia volubilis* L. as a traditional food from a third country pursuant to Article 14 of Regulation (EU) 2015/2283, 2020, doi:10.2903/sp.efsa.2020.EN-1817.
77. Srichamnong, W.; Ting, P.; Pitchakarn, P.; Nuchuchua, O.; Temviriyanukul, P. Safety assessment of *Plukenetia volubilis* (Inca peanut) seeds, leaves, and their products. *Food Sci. Nutr.* **2018**, *1–8*, doi:10.1002/fsn3.633.
78. Vašek, J.; Cepková, P.H.; Viehmannova, I.; Ocelák, M.; Cachique, D.H.; Vejl, P. Dealing with AFLP genotyping errors to reveal genetic structure in *Plukenetia volubilis* (Euphorbiaceae) in the Peruvian Amazon. *PLoS ONE* **2017**, *12(9)*, e0184259.

 doi:10.20944/preprints202105.0090.v1

79. Jacobsen, S.-E.; Sørensen, M.; Pedersen, S.M.; Weiner, J. Using our agrobiodiversity: plant-based solutions to feed the world. *Agron. Sustain. Dev.* **2015**, *35*, 1217–1235.
80. Funabashi, M. Human augmentation of ecosystems: objectives for food production and science by 2045. *npj Science of Food* **2018**, *2*, 16, doi:10.1038/s41538-018-0026-4.
81. Kodahl, N. Sacha inchi (*Plukenetia volubilis* L.)—from lost crop of the Incas to part of the solution to global challenges? *Planta* **2020***, 251*, 80.