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Can a native cricket species be used as a potential human food source?

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Abstract. Singapore, being land-scarce and lacking in natural resources, has invested immensely in food security. In a new era brought about by the COVID-19 pandemic and anthropogenic climate change, global supply chains can be disrupted easily and the ability to produce food locally becomes even more critical. More recently, there has been greater interest among research organisations and companies to address this by investing in the development of healthier alternative protein sources, i.e., insects (including crickets), which are more environmentally-friendly and can generate higher yield in local, high-tech insect farms. However, typical gryllines—*Acheta domesticus* (Linnaeus, 1758) and *Gryllus bimaculatus* De Geer, 1773 (Gryllidae: Gryllinae)—currently used in insect farming around the region and Singapore are non-native. Hence, they are much more vulnerable to local diseases, less adaptable to the local climate, can create problems associated with invasive species and are affected by global supply chain disruptions. Here, we propose that a native cricket species, i.e., *Lebinthus luae* (Gryllidae: Eneopterinae), could be used as a potential candidate to be reared in farms for food and broaden our diversity of protein sources. *Lebinthus luae* has advantages over conventional non-native crickets because it is micropterous (higher energy allocated to body growth) and does not cause acoustic nuisance. However, we also found that the female fecundity and fertility are lower and the emergence time is longer than the aforementioned species (i.e., gryllines). We conclude that the life cycle assessment under farming conditions is still needed for this species. Harvesting of wild *Lebinthus luae* for human consumption is not feasible and legislation must also be put in place to prevent unlawful and unethical harvesting of these crickets. We should therefore be mindful of unintended consequences of habitat damage and species loss due to unsustainable and unethical harvesting of native species despite the good intentions of using a native species to avoid problems associated with invasive species.

Key words. Fecundity, fertility, food security, Gryllidae, invasive species, Singapore

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INTRODUCTION

Entomophagy, the consumption of insects, is practised in many parts of the world and already has a long history in some countries and cultures (Ramos-Elorduy, 2009; van Huis, 2013; Raheem et al., 2019). In other parts of the world where insects are not traditionally consumed, entomophagy has also gained popularity in recent times (Ramos-Elorduy, 2009; Raheem et al., 2019). This is because there are growing concerns that conventional food production can no longer sustain the growing demand for food caused by human population growth. Increasing scarcity of arable land, climate change and poverty call for a cheaper, healthier, more sustainable, alternative form of food production (van Huis, 2013, 2015; van Huis & Oonincx, 2017). Consequently, culturing insects for food has been lauded as a solution to this global problem. The most commonly consumed insects are often from the most abundant and species-rich orders of insects—the orders Coleoptera, Lepidoptera, Hymenoptera and Hemiptera (Yhoung-Aree et al., 1997; Sun-Waterhouse et al., 2016; Raheem et al., 2019).

Nevertheless, both adults and nymphs of Orthoptera are also among the most commonly consumed insects (Sun-Waterhouse et al., 2016; Raheem et al., 2019). This is most likely attributed to various benefits of orthopterans as a food source: 1) high feed conversion efficiency, 2) readily reared on agricultural by-products (e.g., weeds, soybean discard), 3) high nutritional content and 4) offering a solution to pest control (Miech et al., 2016; Magara et al., 2019; Boulos et al., 2020; Quek et al., 2020). Among the 29,000 species of crickets, grasshoppers and katydids worldwide (Cigliano et al., 2022), orthopterans from the cricket families Gryllidae and Gryllotalpidae are the most popular as food (Yhoung-Aree et al., 1997; Sun-Waterhouse et al., 2016; Magara et al., 2021). Specifically, as many as 60 species of crickets are reported to be edible (Sun-Waterhouse et al., 2016; Magara et al., 2021).

In Singapore, entomophagy is not a tradition and remains an unusual practice among locals. However, the land-scarce city state also recognises the potential importance of insects as part of the diet in this new era brought about by the COVID-19 pandemic and anthropogenic climate change (on the condition that their safety for human consumption is well documented and approved). The ability to be self-sufficient in food production has become more important because global supply chains can be disrupted easily by pandemics and natural disasters in other parts of the world. To achieve self-sufficiency, there is great potential in using crickets as an alternative protein source (Leow, 2019). As a result, relatively new local businesses that sell insect/cricket-made products have emerged (Paulo & Ong, 2020; Sundar, 2021; Tan, 2021). There are also programs to develop insect farms for animal feed.

These businesses in Singapore are still dependent on the import of processed crickets (cricket "flour") from neighbouring countries and can still be affected by global supply chain disruptions. More critically, the species *Acheta domesticus* (Linnaeus, 1758)—the most widely consumed cricket globally (Magara et al., 2021)—is being used, but this is a non-native species in Singapore. Another non-native species often reared in cricket farms for food is *Gryllus bimaculatus* De Geer, 1773. The origins of these species are not entirely clear, although they are generally thought to have originated from arid to semi-arid areas of Southwestern Asia and/or northern Africa, and subsequently spread all around the world by humans (Ghouri, 1961; Ferreira & Ferguson, 2010). These exotic species are likely to be less adaptable to the local humid tropical climate, more vulnerable to local diseases and more likely to cause ecological impacts associated with invasive species. Although *Acheta domesticus* and *Gryllus bimaculatus* are sold as fish feed in most aquarium shops around Singapore and sometimes used illegally for mercy-release purposes (Ang & Tan, 2018), cricket production for human consumption at a much larger scale can potentially increase the risks of the aforementioned problems.

To minimise the potential threats posed by these non-native cricket species as well as to reduce the dependency on imports and a global supply chain, we propose to explore the use of cricket species native to Singapore as human food. There are at least 64 species of crickets (superfamily Grylloidea) reported in Singapore (Tan, 2012, 2017). Although many species are restricted to forests, are rare (low in abundance and/or limited in distribution) and/or even endemic (e.g., Gorochov & Tan, 2012; Tan & Robillard, 2014; Tan & Kamaruddin, 2016; Gorochov et al., 2018), some species are more widespread and abundant in both Singapore and the surrounding region. Based on a set of criteria and current knowledge of the crickets in Singapore, we present a candidate species to serve as a test bed for farming native species for food: *Lebinthus luae* Robillard & Tan, 2013 (Gryllidae: Eneopterinae: Lebinthini: Lebinthina). We then present its distribution in Singapore based on literature and specimen records (both physical and online citizen-science data). As the female fecundity and fertility of this species has not been reported, experiments were conducted on wild individuals to examine the number of eggs produced and the emergence time and rate. We then discuss the prospect of using this species as an alternative protein source in Singapore.

MATERIALS AND METHODS

Candidate species. From the recent checklists of crickets in Singapore (Tan, 2012, 2017), candidate native species were selected based on the following criteria:

1) Widely distributed and abundant locally in Singapore (i.e., not endangered) to prevent local extinction owing to harvesting of wild crickets;
2) Apterous or micropterous so that more energy is allocated to body growth instead of wings, and hence potentially higher protein content than macropterous species;
3) Body size comparable to commonly reared species (ca. 20 mm);
4) Adaptable to captive environment and easily reared (e.g., generalist diet);
5) Does not cause acoustic nuisance typical of *Acheta domesticus* and *Gryllus bimaculatus.*

Distribution. The distribution of the candidate species in Singapore was determined using specimen records based on published literature review, specimens deposited in the Zoological Reference Collection (ZRC, Lee Kong Chian Natural History Museum, Singapore), iNaturalist records and unpublished personal observations.

Female fecundity and fertility. To examine the female fecundity (number of eggs produced) and fertility (number of fertilised eggs produced), 30 adult females were opportunistically collected from the wild and reared in single-female set ups to facilitate egg collection (Fig. 1). Dried dog food (25% crude protein) was provided as food. Females were provided with two moist, folded cotton pads that were replaced weekly for a period of three weeks between 27 September and 17 October 2021. The number of eggs laid by each female was counted and recorded as soon as the cotton pads were removed from the female containers. The egg-laden cotton pads from each female were combined and held in a separate plastic container. This "egg" container was checked weekly for the presence of new emergence. The total number of successful emergences was recorded and are provided as a percentage of total number of eggs laid.

Fig. 1. Set up that accommodates a single female. The two cotton pads were both water sources and used for collecting eggs. (Photograph by: D. Tan).

RESULTS AND DISCUSSION

Candidate species. We propose the following candidate species that can be reared in insect farms for human food: *Lebinthus luae* (Fig. 2). The adults (female adult body length = 17.4 mm) are of similar size to *Acheta domesticus* but both males and females are micropterous (rather than fully winged). The males produce high-frequency calls (Robillard & Tan, 2013). The Muséum national d'Histoire naturelle, Paris has successfully maintained a colony under laboratory conditions, indicating that this species can adapt well to a captive environment. Both nymphs and adults feed readily under captivity on different food items (e.g., live plants, dog food pellets, whole grain cereals) (Ballesteros et al., 2022), while in the wild, they feed opportunistically on leaves and fruits of a variety of plant species near the forest floor (Robillard & Tan, 2013). Other possible candidate species include *Velarifictorus aspersus* (Walker, 1869) and *Mitius* species (both Gryllidae: Gryllinae) and *Nisitrus malaya* Robillard & Tan, 2021 (Tan et al., 2021). While these species are also abundant, widespread, adaptable to a captive environment and easily reared, they are macropterous and produce lower frequency calls that are more typical of *Acheta domesticus* and *Gryllus bimaculatus* (Tan, 2020) compared to *Lebinthus luae*.

Distribution. *Lebinthus luae* is a widely distributed species of eneopterine cricket in Southeast Asia. In addition to Singapore, it can be found in Indonesia (Java, Sumatra), Palau, Peninsular Malaysia, East Malaysia (Sabah), and the Philippines (Robillard & Tan, 2013; Robillard & Yap, 2015; Baroga-Barbecho et al., 2020). Within Singapore, *Lebinthus luae* is limited to a few isolated populations in the Sungei Buloh Wetland Reserve, the northeastern coast, the Bukit Timah area, the southern ridges and the southern islands (Tan, 2010, 2012, 2013, 2017; Tan & Wang, 2012; Tan et al., 2012; Robillard & Tan, 2013) (Fig. 3). Although *Lebinthus luae* can be found in different parts of Southeast Asia and Singapore, Tan (2017) listed *Lebinthus luae* as a vulnerable species in Singapore. This is attributed to the fact that the populations in Singapore are isolated and their habitats can be highly disturbed (Tan & Robillard, 2021). As such, harvesting of wild *Lebinthus luae* for human consumption is not feasible and may cause populations to go extinct locally. Even if *Lebinthus luae* is to be collected for large-scale cricket production in the farms, impact assessment is of paramount importance. Population size, habitat size, disturbance levels of habitats and potential threats to each population must be considered to understand the vulnerability of each population to local extinction. Legislation must also be put in place to prevent

Fig. 2. A male (left) and female (right) *Lebinthus luae* interacting on foliage in their natural environment. (Photograph by: B. Yeap).

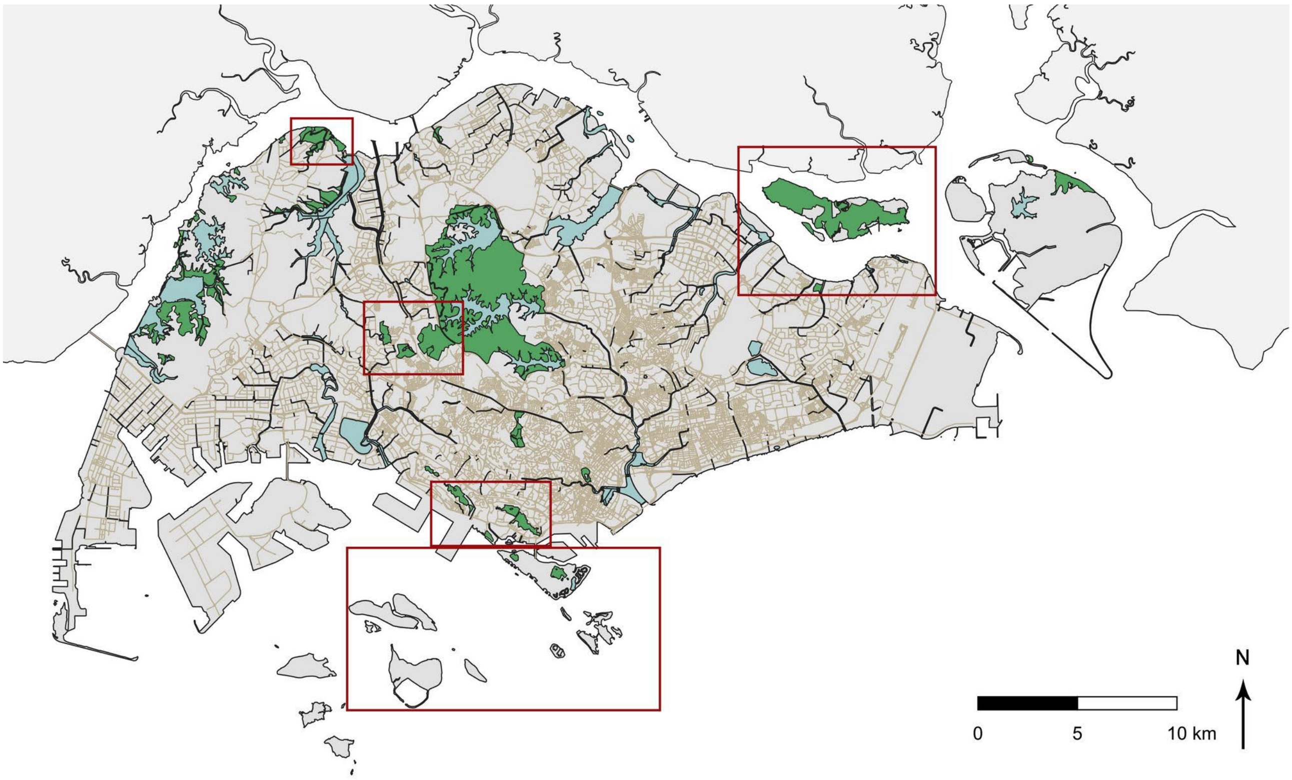

Fig. 3. Map of Singapore showing the distribution of *Lebinthus luae*. The exact locations are not revealed here to prevent illegal collection/ harvesting and exploitation of *Lebinthus luae*.

unlawful and unethical overharvesting of these crickets from natural habitats and damaging the fragile and fragmented environment that these crickets inhabit.

Female fecundity and fertility. Female fecundity of crickets can be influenced by numerous factors such as diet and environmental conditions (e.g., Gutiérrez et al., 2020). However, this is more rarely reported for species used for cricket

Fig. 4. A female ovipositing on the moist, folded cotton pad. (Photograph by: D. Tan).

rearing compared to growth rate and survival probability (but see Clifford & Woodring, 1990). Here, we present baseline values of the female fecundity of *Lebinthus luae* for the first time.

In our experiments, all 30 females oviposited over the three weeks, despite seven of the 30 females having died prematurely before the end of three weeks. Two individuals which died prematurely oviposited less than 20 eggs and one oviposited only one egg. We considered the latter individual as an outlier and removed this individual from the subsequent analyses. At an average temperature of 28.4°C and relative humidity of 78.7%, a single female can lay ca. 89±45 eggs (18–183 eggs) on average in three weeks (N = 29 females, excluding the female that produced only one egg), amounting to an average of four eggs laid daily per female (Figs. 4, 5a). This demonstrates that *Lebinthus luae* readily oviposits in captivity.

In total, 2,587 eggs were counted (N = 29 females). Within a period of four weeks between 18 October and 14 November 2021, 1,203 nymphs emerged (46.5% of total eggs counted) (Fig. 6). This also suggests that a female can produce an average of 41 fertilised eggs over a period of three weeks. The highest emergence occurred between 25 and 30 October (430 nymphs emerged), indicating that the nymphs in general took an average of three weeks to emerge (since the highest number of eggs laid, i.e., 1,038 eggs, occurred between 4 and 10 October) (Fig. 5b).

Our findings indicate that *Lebinthus luae* has a lower female fecundity and fertility and a longer emergence time compared to *Acheta domesticus, Gryllus bimaculatus* and other gryllines used for human feed. Typically, the aforementioned gryllines take about two weeks for nymphs to emerge and each female can also produce more eggs per day (Clifford & Woodring, 1990; Magara et al., 2019; Kim et al., 2020). Granted, the wild-caught/experimental *Lebinthus luae* females used in our experiments may have lower fecundity and fertility because of less-than-ideal conditions (e.g., poorer nutrition, diseases and injuries in the wild, as well as stresses from the change of environment). The age of the females, which affects fecundity and fertility (Zuk, 1988; Zajitschek et al., 2009), is also unknown since the females were collected opportunistically. Our findings and the high variation in the eggs produced are perhaps more representative of natural or semi-natural fecundity and fertility rather than the potential fecundity under more controlled and optimised conditions.

Acoustics/noise. The intensity of orthopteran calls is not trivial. In 2016, United States diplomats in Cuba experienced ear pain, tinnitus and cognitive difficulties after seemingly being exposed to the calls of *Anurogryllus celerinictus* Walker, 1973 (Stubbs & Montealegre-Z, 2019). When housed in high density in insect farms, the low-frequency calls of *Acheta domesticus* and *Gryllus bimaculatus*—dominant frequency at around 4.5–5.5 kHz, within the human audible range (Stout et al., 1988; Kostarakos et al., 2009; Montealegre-Z et al., 2011; Miyashita et al., 2016; Tan, 2020)—can pose an acoustic nuisance. The dominant frequency of calling song of *Lebinthus luae* is 18.3±0.7 kHz (16.8–18.9 kHz) which is drastically

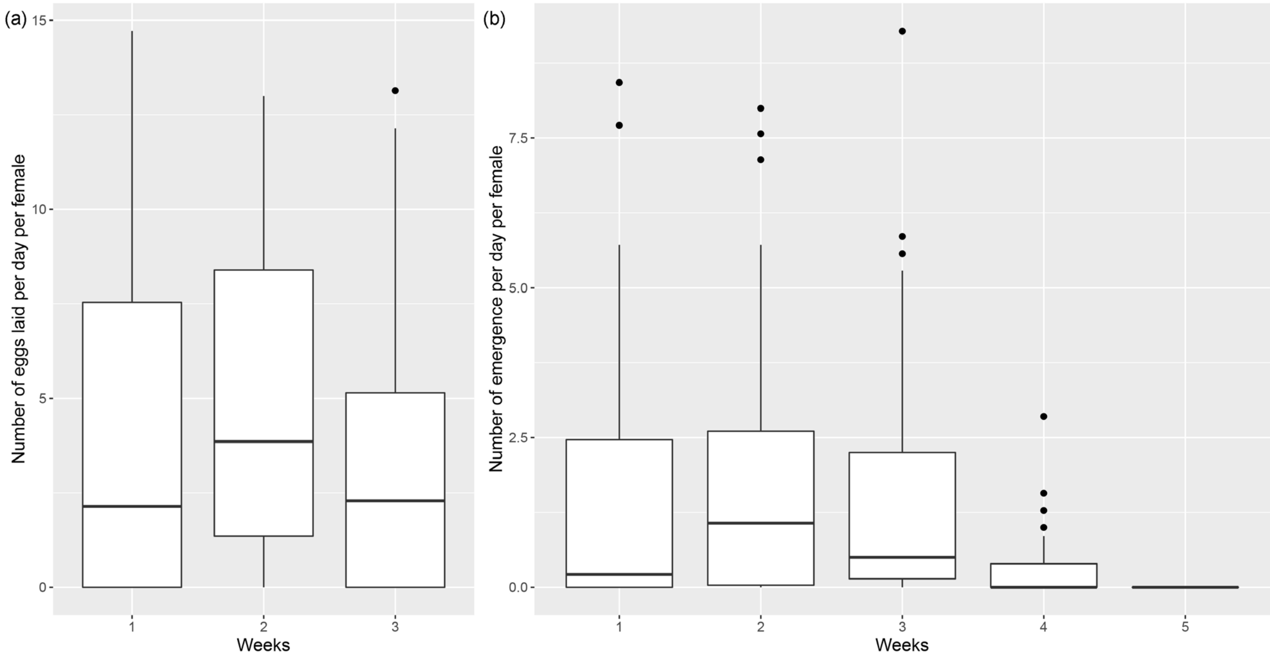

Fig. 5. Box plots showing the (a) number of eggs laid daily per female counted for a period of three weeks between 27 September and 17 October 2021 and (b) number of emergences daily per female for a period of five weeks (post egg-collection) between 18 October and 21 November 2021. The horizontal bar shows the median; lower and upper margins of the box indicate the inter-quartile range and whiskers refer to the minimum and maximum data points; each black dot represents an outlier.

Fig. 6. A one-day old nymph of *Lebinthus luae*. Approximate body length = 2 mm. (Photograph by: M. K. Tan).

higher than both *Acheta domesticus* and *Gryllus bimaculatus*. This indicates that the calls of *Lebinthus luae* are near-ultrasonic and hence, barely audible to humans. This can be viewed as a major benefit of using this species for farming as there would be fewer concerns about acoustic nuisance.

Other considerations. We hitherto do not have detailed information on the growth and survival of *Lebinthus luae* under laboratory conditions and under different diet treatments. Nevertheless, this species typically takes about four to six months for nymph maturation to the adult form when fed ad libitum with a mixed diet of high protein dog food, cereal and leaves and kept in large community tanks. However, this is drastically longer than that of *Acheta domesticus, Gryllus bimaculatus* and other gryllines (Fernandez-Cassi et al., 2019). This may not be a beneficial factor when using *Lebinthus luae* as human food owing to its long harvesting cycle.

One of the benefits proposed by proponents of cricket consumption is that harvesting of wild crickets is a means of pest control. Consumption of crickets can protect field crops and household plants while reducing pesticide use to control cricket pests (Magara et al., 2021). However, there have not been any reports on *Lebinthus luae* as a pest in Singapore or the rest of its distribution. These detritivores are likely to play important roles in the ecosystem by feeding on decaying fruits and plant parts (Robillard & Tan, 2013) and possibly helping with nutrient-recycling processes.

Factors such as energy and water consumption and greenhouse gas emissions, feed conversion ratio and nutrient content, as well as waste management and nutrient recycling are important practical considerations when selecting a species for large-scale commercial farming (Halloran et al., 2016). Our postulation is that *Lebinthus luae* may possess a protein and/or fat content that is higher than typical gryllines because of its microptery (i.e., the absence of fully developed wings for flight) since more resources could be invested in the other body parts. However, this needs to be confirmed with a nutrient profile analysis that is not currently available. These factors will need to be addressed in future but are currently out of the scope of this paper.

Lastly, Singaporeans' perception and attitudes towards consuming crickets, and specifically native crickets, is also crucial for insect farms and insect consumption to take root in Singapore. Although entomophagy is not new to many Asian countries (Yen, 2015), entomophagy is met with aversion in many countries with no previous exposure to insects as food, including in Singapore (e.g., Barton et al., 2020; Burt et al., 2020; Tuccillo et al., 2020; Ardoin et al., 2021; Wendin & Nyberg, 2021). A native, wild species such as *Lebinthus luae* may also be avoided owing to a perceived similarity to 'game' meat. However, the processing of grylline crickets (e.g., milling the cricket into 'flour') for incorporation into mainstream food products such as energy bars and baked confectionary can make it more palatable to the local population (Tan, 2021; Trang, 2021). In Thailand, restaurateurs have taken it a step further, marketing insect food as a premium in fine-dining to entice those with an adventurous palate and greater expendable income (Board, 2019). The focus on food security and alternative protein in Singapore, coupled with extensive public education efforts, should aid public acceptance as it continues to expand the green consumer market.

Conclusions. Although using the native *Lebinthus luae* as a potential human food has its advantages over non-native, conventional feed species, there are also potential disadvantages such as lower female fecundity, fertility and a longer life cycle. The prospect of *Lebinthus luae* as a human food in the future relies on further research on the life cycle assessment under farming conditions. It also depends on the will of farming companies to achieve a balance between sustainability, invasive species threats, conservation, economic/ commercial profit and food safety. In the light of the unknowns and uncertainties mentioned above, it is still too early to specifically recommend the use of *Lebinthus luae* as a protein source in Singapore. However, this investigation also aims to demonstrate that knowledge of local biodiversity (particularly insects) can be leveraged to meet Singapore's ecological sustainability and food security goals. Most critically, whilst reliance on native cricket species to avoid potential problems caused by invasive cricket species is well-intentioned, we should also avoid the unintended consequence of habitat damage and species loss due to unsustainable and unethical harvesting of native cricket species.

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