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Occurrence and unlimited spread of *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) in Tanzania: A potential economic threat to the citrus industry

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ABSTRACT

Citrus production is a cornerstone of Tanzania's agricultural sector, supporting economic development and food security. However, the industry faces a critical threat from the Asian citrus psyllid (*Diaphorina citri* Kuwayama), the primary vector of the destructive Huanglongbing (HLB) disease. This study investigates the distribution, abundance, and environmental drivers of *D. citri* and the African citrus triozid (*Trioza erytreae*) in major citrus-growing regions of Tanzania. Surveys conducted between March and May 2023 revealed the presence of *D. citri* in the Tanga and Morogoro regions, including the first documented occurrence in the Tanga region. Conversely, *T. erytrae* was confined to the Arusha region. Altitude emerged as a significant factor influencing psyllid abundance. *D. citri* populations decreased with increasing altitude, while *T. erytrae* exhibited the opposite trend. Temperature also showed correlations with psyllid populations, though additional research is needed to fully elucidate these relationships. Citrus variety significantly influenced *D. citri* abundance, with Late Valencia (Kitenesi) being the most susceptible. Importantly, several varieties showed no presence of *D. citri*, offering potential sources of resistance. The intensity of new flush growth was strongly correlated with psyllid abundance. These findings highlight the urgent need for region-specific and altitude-tailored citrus pest management strategies. The identification of potentially HLB-resistant citrus varieties provides a promising avenue for breeding programs. This research offers critical insights to protect Tanzania's citrus industry and ensure the sustainable production of this vital economic crop.

Keywords: Citrus, Citrus greening, *Diaphorina citri* Kuwayama, Huanglongbing, *Trioza erytreae*, Distribution, Altitude, Tanzania

RÉSUMÉ

Présence et propagation illimitée de *Diaphorina citri* Kuwayama (Hemiptera : Liviidae) en Tanzanie : une menace économique potentielle pour l'industrie des agrumes

La production d'agrumes est un pilier du secteur agricole de la Tanzanie, soutenant le développement économique et la sécurité alimentaire. Cependant, l'industrie fait face à une menace critique du psylle asiatique des agrumes (*Diaphorina citri* Kuwayama), le principal vecteur de la maladie destructrice du Huanglongbing (HLB). Cette étude examine la distribution, l'abondance et les facteurs environnementaux qui influencent *D. citri* et le trioze africain des agrumes (*Trioza erytreae*) dans les principales régions productrices d'agrumes de la Tanzanie. Des enquêtes menées entre mars et mai 2023 ont révélé la présence de *D. citri* dans les régions de Tanga et de Morogoro, y compris la première occurrence documentée dans la région de Tanga. Au contraire, *T. erytrae* était confiné à la région d'Arusha. L'altitude s'est révélée être un facteur significatif influençant l'abondance des psylles. Les populations de *D. citri* diminuaient avec l'augmentation de l'altitude, tandis que *T. erytrae* présentait la tendance inverse. La température a également montré des corrélations avec les populations de psylles, bien que des recherches supplémentaires soient nécessaires pour élucider pleinement ces relations. La variété d'agrumes a influencé de manière significative l'abondance de *D. citri*, avec la Late Valencia (Kitenesi) étant la plus sensible. Plus important encore, plusieurs variétés n'ont montré aucune présence de *D. citri*, offrant des sources potentielles de résistance. L'intensité de la croissance des nouvelles pousses était fortement corrélée à l'abondance des psylles. Ces résultats soulignent la nécessité urgente de stratégies de gestion des ravageurs des agrumes spécifiques à la région et adaptées à l'altitude. L'identification de variétés d'agrumes potentiellement résistantes au HLB offre une voie prometteuse pour les programmes de sélection. Cette recherche offre des perspectives critiques pour protéger l'industrie des agrumes de la Tanzanie et assurer la production durable de cette culture économique vitale.

Mots clés : Agrumes, Verdissement des agrumes, *Diaphorina citri* Kuwayama, Huanglongbing, *Trioza erytreae*, Distribution, Altitude, Tanzanie

INTRODUCTION

Citrus fruits are a major global crop, valued for their nutritional benefits and economic importance (FAO, 2021). Their high content of phytonutrients and bioactive compounds promotes health and boosts immunity (Liu *et* al., 2022). The demand for citrus fruits, especially oranges and lemons, has surged during the COVID-19 pandemic as consumers aim to increase their vitamin C intake (Andrade-Cuvi *et al*., 2023; Moreb *et al*., 2021). According to Reportlinker (2023), increased demand from both domestic and foreign markets will drive global citrus production to over 160 million tons by 2027. Brazil, China, the United States, India, and Mexico are among the major citrus-producing countries (FAO, 2022). In Africa, citrus cultivation plays a significant role in food security, employment, and export revenue. Within East Africa, Tanzania, Kenya, and Uganda play significant roles as key citrus producers (FAO, 2021). Tanzania's citrus production is steadily increasing, primarily in regions like Morogoro, Tanga, Kilimanjaro, and Coast (ESRF, 2021). Citrus farming provides direct and indirect employment opportunities, supporting the livelihoods of many rural communities and contributing to the country's agricultural and economic growth (URT, 2021). Despite its potential, the citrus industry faces significant challenges, including limited access to high-quality planting materials, poor post-harvest practices, and inadequate infrastructure (Aminu *et al*., 2020). Furthermore, insect pests and diseases pose a constant threat to citrus production (Makorere, 2014). Among these pests, citrus psyllids are a major concern due to their ability to transmit the incurable Huanglongbing (HLB) disease (Bove, 2006). HLB, caused by bacterial pathogens (*Candidatus* Liberibacter spp.), is a devastating citrus disease with no known cure (Garnier *et al*., 1984a, 1984b). The disease has resulted in significant economic losses in citrus-growing regions worldwide (Singerman & Useche, 2019). Two insect vectors—the African citrus triozid (*Trioza erytreae*) and the more destructive Asian citrus psyllid (*Diaphorina citri* Kuwayama)—transmit the pathogens (Graça & Korsten, 2004). The global movement of people and goods has helped the spread of HLB and its carriers, posing a significant threat to citrus production worldwide (Gottwald *et al*., 2007). In recent years, the spread of *Diaphorina citri* Kuwayama in Tanzania has increased the risk of HLB becoming widely established in the country and across Africa. *Diaphorina citri* Kuwayama was first detected in Eastern Africa during surveys conducted in Tanzania in 2014 and 2015 (Shimwela *et al*., 2016). Predictive models indicate that large areas of coastal Tanzania provide favorable conditions for the establishment of *D. citri* (Rwomushana *et al*., 2017). The significant losses incurred in other affected regions show that the potential economic impact of HLB on the citrus industry for Tanzania could be severe (de Oliveira *et al*., 2013). Efficient monitoring of *D. citri* is crucial for early detection, allowing prompt intervention and the use of customized pest control methods to protect the citrus industry (Grafton-Cardwell *et al*., 2013; Rogers & Stansly, 2007). However, there is a significant lack of knowledge about the current distribution and abundance of *D. citri* in Tanzania's citrus-growing regions. This study aims to fill this gap by conducting systematic assessments to explore the presence and spread of *D. citri* in key citrus production areas of Tanzania. The results will provide crucial insights, such as *D. citri* distribution patterns, population dynamics, and hotspot areas, which will assist citrus stakeholders in developing targeted pest control strategies to safeguard Tanzania's citrus sector.

Materials and methods

Study site

The study was carried out in four discrete regions of Tanzania. These are Ruvuma, located at coordinates -10.7000 latitude and 36.2333 longitude; Arusha, situated at coordinates -3.3667 latitude and 36.6833 longitude; Morogoro, positioned at coordinates -6.8210 latitude and 37.6612 longitude; and Tanga, found at coordinates -5.0689 latitude and 39.0988 longitude. The selection of these regions was based on their citrus production records and the different altitudes they have, as altitude is a crucial factor that affects the distribution and diversity of citrus psyllids (Jenkins *et al*., 2015). The chosen regions encompass a variety of elevations: Tanga for low elevations (300 m), Morogoro and Ruvuma for moderate elevations (ranging from 300 m to 900 m), and Arusha for high elevations (exceeding 900 m).

Surveys and sample collection

Citrus surveys were conducted from March to May 2023. One district was chosen from each region based on citrus production records and farm availability. Ten citrus farms were randomly selected per district to ensure a representative sample. GPS coordinates (latitude, longitude) and altitude were recorded for each farm. In orchards smaller than 0.5 hectares, all citrus trees were assessed. In larger orchards, 10 trees were selected at regular intervals. On each tree, one new shoot was randomly selected from each of the four cardinal points and examined for citrus psyllids. Special attention was paid to leaf galls indicative of *Trioza erytreae*, particularly at higher altitudes. Collected psyllids were preserved in ethanol for identification and analysis.

Psyllid Identification

Initial identification of psyllids involved using a hand lens. Psyllids with a mottled brown or greyish-brown body, light brown head, and probing at a steep angle were identified as *Diaphorina citri* Kuwayama (Figure 2). Meanwhile, probing at a less steep angle, black-headed psyllids with transparent wings were identified as *T. erytrae* (Figure 3), per Shimwela *et al*. (2016). Nymphs with a white, waxy secretion and light-yellow colour with red eyes were identified as *Diaphorina* sp. Conversely, *T. erytrae* nymphs had brown eyes and, sometimes, a pair of spots on the base of the abdomen in the late stages. *Trioza erytreae* nymphs were generally found in puckered galls on the leaves.

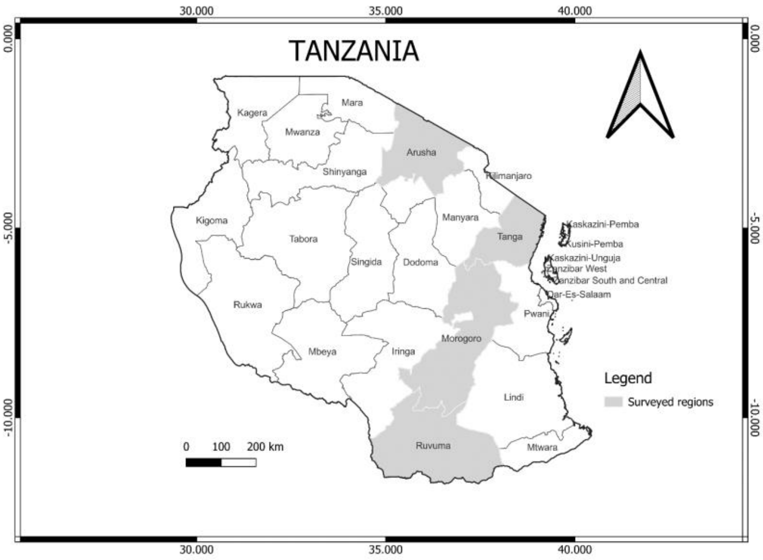

Table 1. Description of selected products used in the study

Psyllid detection and identification
Total DNA was extracted from psyllid specimens using the CTAB protocol. DNA concentration and purity were assessed using a Nanodrop spectrophotometer. For species confirmation, a portion of the mitochondrial cytochrome oxidase I (mtCOI) gene was amplified by conventional PCR using the DCITRI COI primers (Boykin *et al*., 2012) (Table 1). The PCR protocol was as follows:
Reaction mixture: (10 µL total) 1x PCR buffer, 0.2 mM dNTPs, 1 µL DCITRI COI primers.

Cycling conditions: 94°C/3 min (initial denaturation); 35 cycles of [94°C/30 sec, 60°C/30 sec, 72°C/1 min]; 72°C/10 min (final extension).
PCR products were visualized on a 1.2% agarose gel (120V, 1.5 hrs) stained with ethidium bromide, using a 1000bp ladder for size comparison. This yielded an expected 834-bp fragment for *Diaphorina citri Kuwayama* (Fujiwara *et al*., 2017).

Table 2. Set of primers used to detect DNA on *Diaphorina citri Kuwayama* Kuwayama.

S/N	Coding region	Primer Sequence		PCR product size
1	mtCOI	DCITRI (5′-AGGAGGTGGAGACCCAATCT-3′)	COI-L	834 bp
		DCITRI (5′-TCAATT GGGGGAGAGTTTTG-3′)	COI-R	

Data analysis
Spatial analysis and mapping of citrus farm distribution were performed using QGIS (version 3.30.2). Descriptive statistics (mean, median, standard deviation, range) were calculated for variables including altitude, temperature, and psyllid abundance. Correlation and linear regression analyses were conducted in R (version 4.3.1) to examine relationships between altitude, temperature, and the abundance of *D. citri* and *T. erytrae*.

RESULTS

Psyllid visual observations
Psyllids with a mottled brown or greyish-brown body, light brown head, and probing at a steep angle were identified as *Diaphorina citri* Kuwayama (Figure 2). Meanwhile, probing at a less steep angle, black-headed psyllids with transparent wings were identified as *T. erytrae* (Figure 3), as per Shimwela *et al*., 2016. Nymphs with a white, waxy secretion and light-yellow colour with red eyes were identified as *Diaphorina* sp. Conversely, *T. erytrae* nymphs had brown eyes and, sometimes, a pair of spots on the base of the abdomen in ate stages. *Trioza erytreae* nymphs were generally found in puckered galls on the leaves.

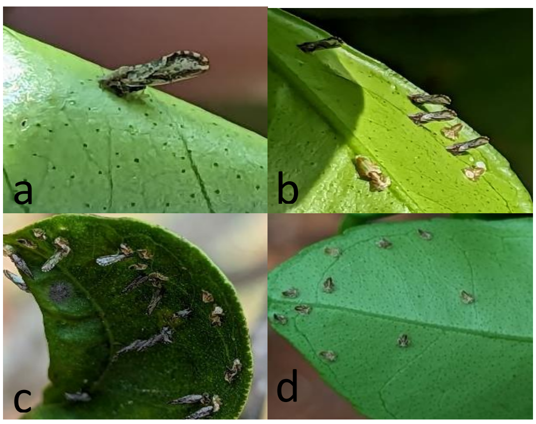

Figure 2. (a) Adult *Diaphorina citri* Kuwayama, (b) and (c) Adult *Diaphorina citri* Kuwayama and its nymphs, (d) The nymphs of *Diaphorina citri* Kuwayama

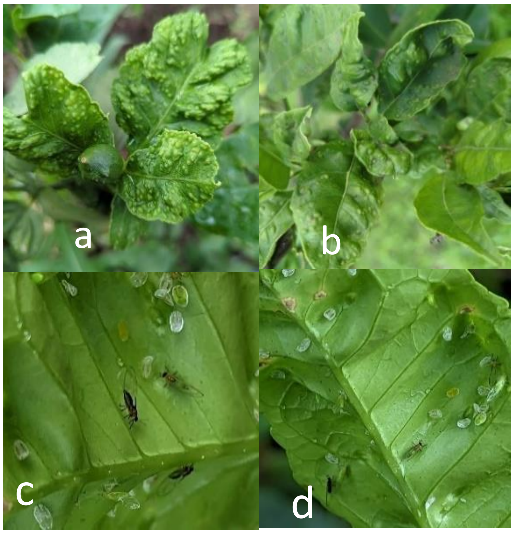

Figure 3. (a) and (b) The leaf galls induced by *Trioza erytreae* on citrus shoots, (c) and (d) *Trioza erytreae* de Guercio with its eggs.

Psyllid molecular identification

Polymerase Chain Reaction (PCR) and agarose gel electrophoresis were utilised to identify *D. citri* in several samples. A 1.2% agarose gel ran at 120V for 1.5 hours. Post the run, ethidium bromide was applied to the gel to enable the visualisation of DNA bands. The specific primers used in the PCR reaction were DCITRI-COI-L and DCITRI-COI-R, specific to *D. citri*. The samples tested were TMF 6-6, TMF 4-1, TMF 6-2, MMF 8-10, MMF 1-1, and TMF 1-0. A molecular weight marker (M) and a negative control (NC) were included in the gel in addition to the samples. The target band was of size 834bp and was visible in the lane labelled "M". This indicated the presence of *D. citri* DNA in those samples (Figure 4).

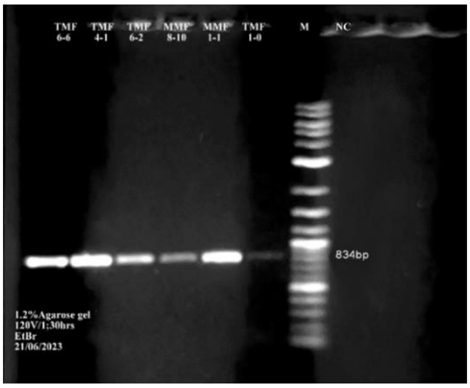

Figure 4. Molecular detection of *Diaphorina citri* Kuwayama.

The distribution of citrus psyllids

This study revealed how the occurrence of *D. citri* and *T. erytrae* in Tanzania varies across different regions. The presence of *D. citri* was limited to the Tanga and Morogoro regions, where it was present in 2 out of 10 sites in Tanga and 5 out of 10 sites in Morogoro (as seen in Table 2). Interestingly, none of the sites in Ruvuma had any *Diaphorina citri* Kuwayama. Conversely, *T. erytrae* was observed in 4 out of 10 sites in Arusha. It was found that the distribution of these pests is region-specific and varies across different areas, as demonstrated by this study (Figure 5).

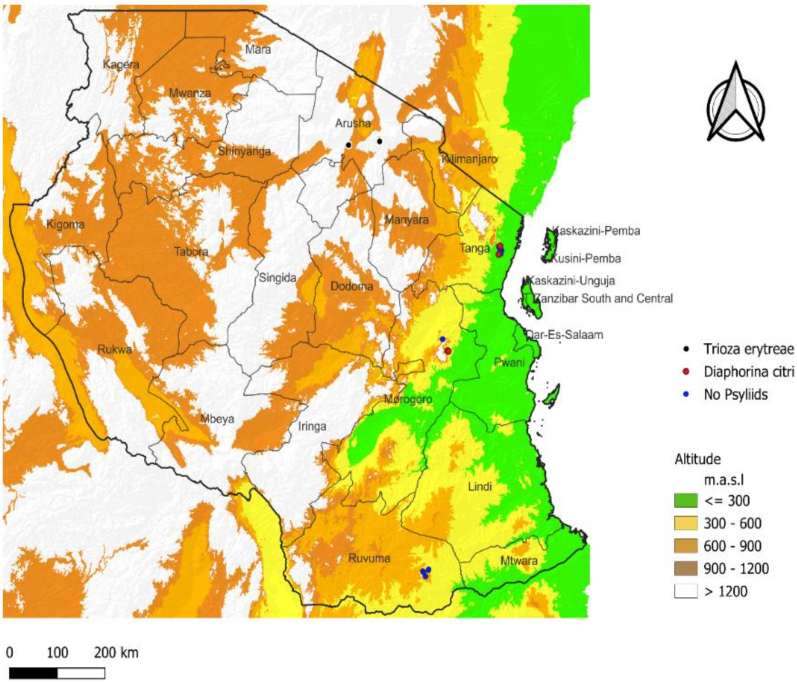

Figure 5. Map of Tanzania showing locations where psyllids surveys were conducted. Blue points: locations where no psyllids were collected; black points: locations where African citrus psyllids (*Trioza erytreae* (del Guercio, 1918)) were observed; red points: locations where Asian citrus psyllids (*Diaphorina citri* Kuwayama) were observed.

Region	Farm number	Ward	Latitude	Longitude	Altitude	Variety	Psyllids Specie	HLB Symptom	Intensity of new flushes
Ruvuma	1	Nakayaya	-10.9879935	37.296125	513.5	Bitijuma	None	Present	High
Ruvuma	2	Nanjoka	-11.0601341	37.337506	664.7	Local variety	None	Absent	None
Ruvuma	3	Nanjoka	-11.0555476	37.33181	660.3	Local variety	None	Absent	Moderate
Ruvuma	4	Kangomba	-10.9797399	37.291018	531.6	Local variety	None	Present	Low
Ruvuma	5	Kangomba	-10.9686599	37.284199	533.8	Local variety	None	Present	Low
Ruvuma	6	Temeke	-10.9412059	37.392876	595.7	Local variety	None	Present	Low
Ruvuma	7	Temeke	-10.9428987	37.392738	593.6	Local variety	None	Absent	Low
Ruvuma	8	Temeke	-10.9447728	37.391446	592.6	Local variety	None	Absent	Low
Ruvuma	9	Temeke	-10.9362276	37.39519	606.3	Local variety	None	Present	Low
Ruvuma	10	Kangomba	-10.9819636	37.290017	548.4	Local variety	None	Absent	Low
Arusha	1	Engutoto	-3.2959374	36.449145	1554.5	Valencia (also known as Msasa)	*Trioza erytreae*	Absent	Low
Arusha	2	Engutoto	-3.3252071	36.45144	1407.1	Local variety	*Trioza erytreae*	Absent	Low
Arusha	3	Engutoto	-3.3260832	36.471876	1486.1	Valencia (Msasa)	None	Absent	None
Arusha	4	Engutoto	-3.3208224	36.448906	1435.8	Valencia (Msasa)	None	Absent	Moderate
Arusha	5	Engutoto	-3.3136255	36.446299	1454.4	Local variety	None	Absent	Low
Arusha	6	Mto Wa Mbu	-3.37901	35.851073	950.9	Washington navel (Kitovu)	*Trioza erytreae*	Present	Moderate
Arusha	7	Mto Wa Mbu	-3.3885351	35.849249	959.8	Local variety	None	Absent	Low
Arusha	8	Mto Wa Mbu	-3.3908645	35.854098	952.0	Valencia (Msasa)	*Trioza erytreae*	Present	High
Arusha	9	Mto Wa Mbu	-3.3866238	35.853506	941.2	Local variety	None	Absent	Low
Arusha	10	Mto Wa Mbu	-3.3701142	35.846101	961.1	Local variety	None	Absent	Low
Tanga	1	Tingeni	-5.1932635	38.74399	197.4	Valencia (Msasa)	None	Present	Low
Tanga	2	Tingeni	-5.1977065	38.759435	208.0	Late Valencia (Kitenesi)	None	Present	Low
Tanga	3	Tingeni	-5.202348	38.769081	179.7	Late Valencia (Kitenesi)	None	Absent	Low
Tanga	4	Tingeni	-5.183548	38.773697	161.8	Late Valencia (Kitenesi)	*Diaphorina citri* Kuwayama	Present	High
Tanga	5	Kwabadi	-5.3243437	38.743933	228.0	Valencia (Msasa)	None	Absent	High
Tanga	6	Kwabadi	-5.3345475	38.746486	191.2	Late Valencia (Kitenesi)	*Diaphorina citri* Kuwayama	Present	High
Tanga	7	Kwabadi	-5.3230697	38.787167	204.6	Valencia (Msasa)	None	Present	Low
Tanga	8	Mtindiro	-5.2688045	38.802039	177.5	Late Valencia (Kitenesi)	None	Absent	Low
Tanga	9	Mtindiro	-5.2649714	38.792234	209.4	Valencia (Msasa)	None	Absent	High
Tanga	10	Mtindiro	-5.2482176	38.768496	238.8	Valencia (Msasa)	None	Present	Moderate
Morogoro	1	Konde	-7.0582139	37.771343	258.6	Valencia (Msasa)	*Diaphorina citri* Kuwayama	Absent	High
Morogoro	2	Konde	-7.0494275	37.765264	257.3	Valencia (Msasa)	*Diaphorina citri* Kuwayama	Present	Moderate
Morogoro	3	Tawa	-7.0525402	37.759583	263.9	Valencia (Msasa)	None	Absent	Low
Morogoro	4	Tawa	-7.0447249	37.763966	270.7	Matombo sweet	*Diaphorina citri* Kuwayama	Absent	Low
Morogoro	5	Konde	-7.0562604	37.762008	268.0	Matombo sweet	*Diaphorina citri* Kuwayama	Absent	Low
Morogoro	6	Konde	-7.0674187	37.766729	326.3	Jaffa (Shamoti)	None	Present	Low
Morogoro	7	Konde	-7.0581612	37.768089	250.2	Matombo sweet	None	Absent	Moderate
Morogoro	8	Konde	-7.0567359	37.777076	293.3	Matombo Sweet	*Diaphorina citri* Kuwayama	Absent	Moderate
Morogoro	9	Mlimani	-6.8410166	37.667829	498.0	Valencia (Msasa)	None	Present	Moderate
Morogoro	10	Mlimani	-6.8428905	37.662237	495.4	Mediterranean (Nairobi)	None	Present	Moderate

Psyllid abundance

The summary statistics revealed that the abundance of *Diaphorina citri* Kuwayama adults varied significantly across the Arusha, Morogoro, Ruvuma, and Tanga regions (p = 0.001). The mean and maximum number of *Diaphorina citri* Kuwayama adults were highest in Tanga, which had 3.45 per region and 86 per farm, respectively. Conversely, Arusha and Ruvuma had no *Diaphorina citri* Kuwayama adults in the sampled areas. The standard deviation was also highest in Tanga (12.19), indicating a high variability in *Diaphorina citri* Kuwayama adults' distribution. A similar pattern was observed for *Diaphorina citri* Kuwayama nymphs, with Tanga having the highest mean (0.5 per region) and maximum (4 per farm) number of *Diaphorina citri Kuwayama* nymphs, while the other regions had none (Figure 6). The abundance of *T. erytrae* adults was low across all regions except for Arusha, which had a mean of 0.153 and a maximum of 9 *T. erytrae* adults. The range and standard deviation of 9 and 1.172, respectively were also highest in Arusha, suggesting a skewed distribution of *T. erytrae* adults. For *T. erytrae* nymphs and eggs (p = 0.190), only Arusha had positive values, with a mean of 2.508 and a maximum of 43.

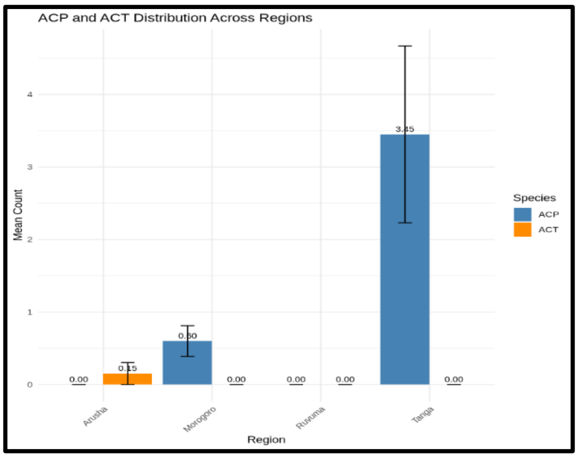

Figure 6. Graph of ACP (Adults and Nymphs) and ACT (Adults and Eggs/Nymphs) against regions

An ANOVA test demonstrated that the regions differed significantly in their abundance of *Diaphorina citri*

Kuwayama adults and *Diaphorina citri* Kuwayama nymphs. However, there were no significant differences among the regions for *T. erytrae* adults or *T. erytrae* nymphs and eggs. The Kruskal-Wallis test, a non-parametric alternative to ANOVA, also confirmed the significant differences in *Diaphorina citri* Kuwayama adult abundance among the regions (p-value = 0.0004). To identify which regions differed significantly from each other, a Tukey's HSD post-hoc test was conducted. The results indicated that Tanga had a significantly higher *Diaphorina citri* Kuwayama adult abundance than Arusha (p-value = 0.0102), Morogoro (p-value = 0.0153), and Ruvuma (p-value = 0.0036). However, no significant differences existed between Arusha and Morogoro, Arusha and Ruvuma, or Morogoro and Ruvuma.

Influence of altitude on psyllid species abundance

The abundance of *Diaphorina citri* Kuwayama nymphs, adults, *T. erytrae* nymphs/eggs, and adults was regressed on altitude using linear regression models. The regression coefficients are presented below in Table 3.

Table 3. Altitude and abundance linear regression coefficients

Character	Intercept	Altitude coefficient
ACP Nymphs Total	0.364	-0.0004***
ACP Adults Total	2.586	-0.0028***
ACT Nymphs and Eggs	-1.083	0.0031***
ACT Adults Total	-0.081	0.0002*

*Note: *** p < 0.001, ** p < 0.01, * p < 0.05*

We found that altitude notably impacts the prevalence of *Diaphorina citri* Kuwayama nymphs, adults, *T. erytrae* nymphs/eggs, and adults. The abundance of *Diaphorina citri* Kuwayama (both nymphs and adults) was lower at higher altitudes, as indicated by significant negative coefficients. Conversely, *T. erytrae* (both nymphs/eggs and adults) exhibited a significant increase in abundance at higher altitudes, as indicated by positive coefficients (Figure 7).

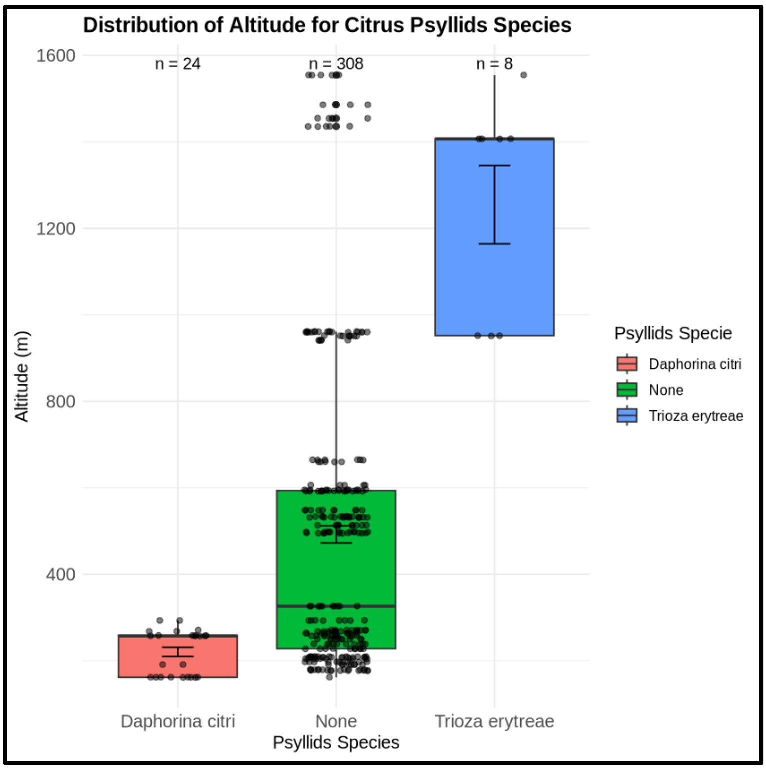

Figure 7. Distribution of altitude for citrus psyllids species

The influence of temperature on Psyllid abundance

A correlation analysis was performed to investigate the link between temperature and *Diaphorina citri* Kuwayama abundance (Table 4). The findings indicated a weak positive correlation between these two variables (r = 0.135), suggesting that higher temperatures were associated with slightly higher *Diaphorina citri* Kuwayama abundance. However, the relationship between the two factors was not particularly strong (Figure 8).

Table 4: Correlation coefficients of temperature and citrus psyllids abundance

Variable	Correlation coefficient	P value
Temperature and *D. citri* abundance	0.135	p < 0.001
Temperature and *T. erytrae* abundance	-0.278	P = 0.0041

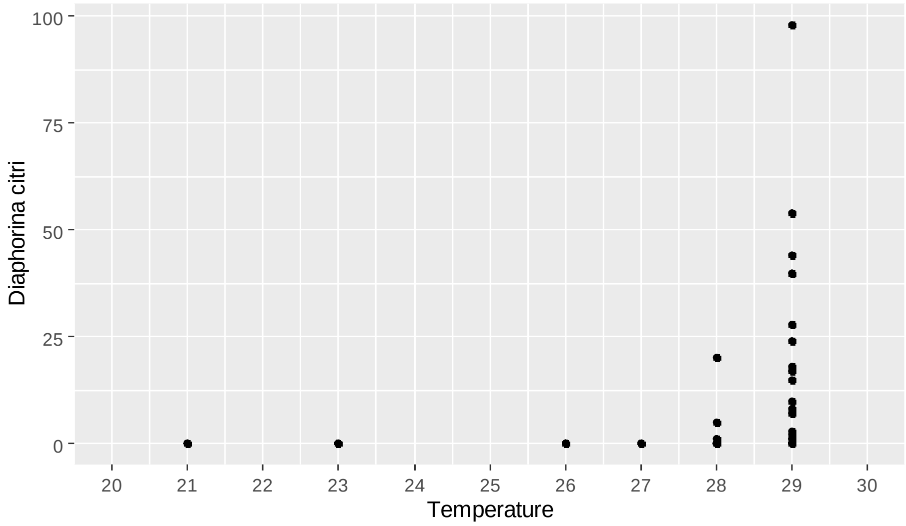

Figure 8. A scatter plot of total ACP adults and Nymphs against temperature

Correlation analysis investigated the link between temperature and *T. erytrae* abundance. The findings indicated a moderate negative correlation (r = -0.278) between the two variables, indicating that higher temperatures were moderately linked to lower *T. erytrae* abundance (Figure 9).

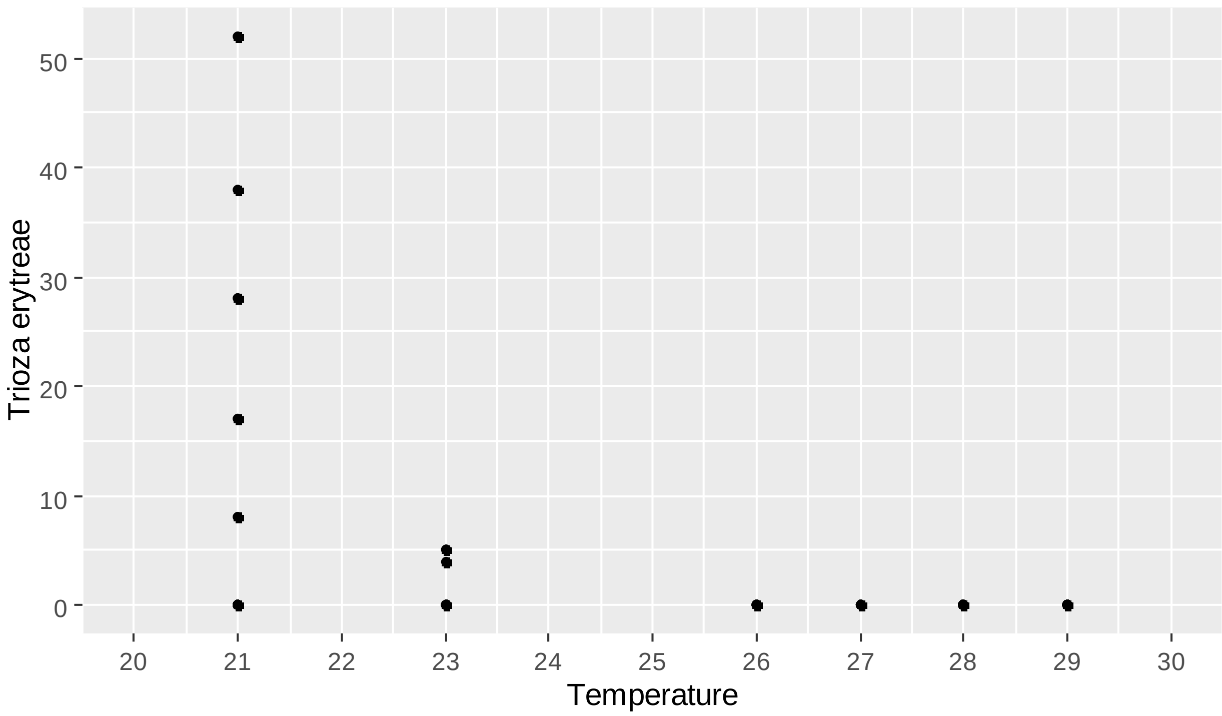

Figure 9. A scatter plot of total ACT adults and Eggs/Nymphs against temperature

The influence of varieties on citrus psyllid abundance

An ANOVA was conducted to assess the impact of different citrus varieties on the abundance of *Diaphorina citri Kuwayama*. The findings indicated a significant effect of variety on *Diaphorina citri Kuwayama* abundance (p < 0.001). Furthermore, Fisher's exact test using simulation suggested a significant relationship between the occurrence of *Diaphorina citri Kuwayama* and the various citrus varieties (p<0.046). Additional analysis was performed to identify the most preferred citrus variety by *Diaphorina citri Kuwayama*. The Late Valencia (Kitenesi) variety had an average of 9.63 *Diaphorina citri Kuwayama* counts per tree, the highest average compared to the other studied varieties (Table 5).

Table 5. The mean *Diaphorina citri* Kuwayama counts per tree on varieties.

S.N	Variety	Mean *D. citri* number per tree	S.E
1	Bitijuma	0.0	0
2	Jaffa (Shamoti)	0.0	0
3	Late Valencia (Kitenesi)	9.634	2.815
4	Local variety	0.0	0
5	Matombo sweet	0.926	0.544
6	Mediterranean (Nairobi)	0.0	0
7	Valencia (Msasa)	0.328	0.123
8	Washington navel (Kitovu)	0.0	0

An analysis was conducted to assess the impact of flush intensity on citrus psyllid count. The findings indicated that trees with high flush intensity exhibited a comparatively greater number of citrus psyllid counts (Figure 10). Conversely, trees with low flush intensity had fewer citrus psyllids.

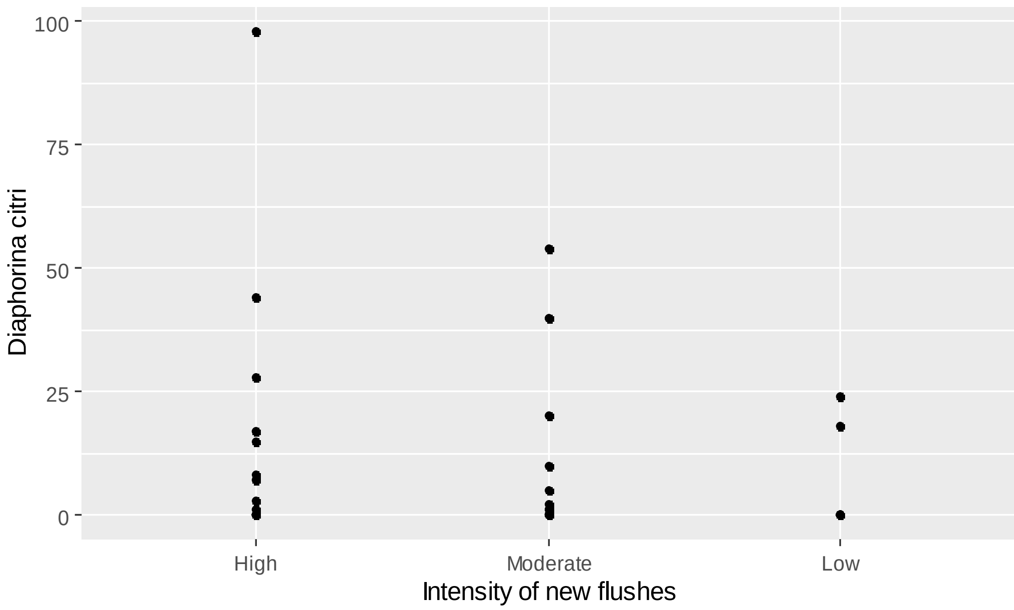

Figure 10. The relationship between *Diaphorina citri* Kuwayama and the intensity of new flushes

DISCUSSION

This study unveils substantial geographical disparities in the presence of *Diaphorina citri* Kuwayama and *Trioza erytreae* within Tanzania. The presence of *Diaphorina citri* Kuwayama in the Tanga region was first recorded in this study, representing the initial documentation of its occurrence in this region. Conversely, *T. erytrae* was confined only to the Arusha region. Various factors contribute to the spread of these insect species across different regions. Among the contributing factors is the potential transportation of citrus plants or infested plant parts, which can serve as vectors for disseminating these insects (Wu *et al*., 2015). Moreover, weather conditions, especially humidity levels, play a crucial role. Elevated humidity levels can significantly impact the survival and reproductive rates of *D. citri* while rendering citrus plants more susceptible to infection by *Candidatus* Liberibacter spp., the pathogens responsible for causing HLB disease (Hall & Hentz, 2011; Yang *et al*., 2006). These populations depend on many factors, such as the weather (Aidoo *et al*., 2022; Wang *et al*., 2020), the number of suitable host plants (Johnston *et al*., 2019), farming methods, and pest control methods (Kuhns *et al*., 2016; Pluke *et al*., 2008). Notably, the observed distribution pattern underscores the wider geographical expanse of *D. citri* in Tanzania compared to *T. erytrae*. These findings have valuable implications for monitoring and managing psyllid populations by shedding light on their spatial dynamics (Grafton-Cardwell *et al*., 2013; Miranda *et al*., 2018). This study has yielded crucial insights into the spatial distribution and population density dynamics of *D. citri* and *T. erytrae* across different Tanzanian regions. The results highlight that *D. citri* predominantly thrives in the Tanga region, exhibiting a notably higher population density than the surveyed regions, as visually depicted in Figure 2.5. It is noteworthy that *T. erytrae* was exclusively detected in the Arusha region. Aidoo *et al*. (2019) have reported more *T. erytrae* populations densities in shaded than unshaded trees. The pronounced variations in psyllid abundance observed among distinct regions within the country underscore the localized nature of these infestations. This highlights the need for region-specific management strategies tailored to each locality's unique dynamics. Vikram Singh and Yadav (2018) highlighted that environmental factors, citrus farming methods, and host plant availability impact the varying abundance of *D.*

citri in different regions. The elevated mean and maximum *D. citri* count in Tanga suggest that this region may provide a more conducive climate or ecological environment for *D. citri* populations. Additionally, Beloti *et al*. (2013) explained that factors like proximity to infested areas, the density of citrus orchards, and the citrus cultivars grown in the area can affect psyllid abundance. The linear regression models employed in this study have yielded compelling evidence of altitude's substantial influence on both *D. citri* and *T. erytrae* populations. Shimwela *et al*. (2016) reported that *D. citri* nymphs and adults exhibit a negative relationship with altitude, indicating a decrease in their abundance with increasing elevation. Conversely, *T. erytrae* nymphs/eggs and adults display a positive relationship with altitude, suggesting an increase in their abundance at higher altitudes, as observed in the study by Shimwela *et al*. (2016). These distinct population patterns can be attributed to factors such as climate preferences, host plant availability, and geographical features. *D. citri*, a species adapted to tropical and subtropical climates, may prefer lower altitudes characterized by warmer temperatures and ample host plant availability. According to Jenkins *et al*. (2015), the associated temperature drop could potentially hinder *D. citri* populations by having an impact on a variety of crucial aspects, such as development, survival, reproduction, or dispersal. On the other hand, according to Aidoo *et al*. (2021), *T. erytrae*, which thrives in cooler environments, may find higher altitudes more favourable for their growth, feeding, and oviposition. This emphasizes the crucial role of altitude in developing integrated pest management plans for citrus psyllids, especially in areas with diverse altitude levels. This newfound knowledge equips farmers and stakeholders in the citrus industry with valuable information to assess the potential risks of psyllid infestations across different altitudinal zones and to implement tailored control measures accordingly. The correlation analysis performed in this study showed intricate relationships between temperature and citrus psyllid abundance. We identified a weak positive correlation between temperature and *D. citri* abundance, indicating that higher temperatures may be linked to increased populations of *D. citri*. However, it is essential to note that the correlation coefficient underscores that temperature alone does not strongly predict *D. citri* abundance. This aligns with previous research highlighting that, while influential, temperature is merely one of several factors ruling citrus psyllid population dynamics. For instance, Chong *et al*. (2010) reported a positive correlation between temperature and psyllid density in young citrus groves, while another study by Tomaseto (2016) suggested that temperature impacts the development and activity of *D. citri*. A moderately negative correlation existed between temperature and *T. erytrae* abundance, suggesting a potential association between higher temperatures and reduced *T. erytrae* populations. While studying similar psyllid species can provide some insights (Zavala-Zapata *et al*., 2022; Tsai *et al*., 2002), a more accurate understanding would be gained by investigating the impact of climate changes on *T. erytrae* in Tanzania. This investigation aims to understand how temperature influences the population growth dynamics of *T. erytrae* in Tanzania, contributing to the broader understanding of climate effects on psyllid populations. Additionally, our study unveiled significant disparities in *D. citri* abundance and occurrence across various citrus varieties. This aligns with prior investigations in other countries that have reported varying susceptibility or attractiveness of citrus varieties to *D. citri* (Eduardo *et al*., 2022; Nehru *et al*., 2004). Notably, the Late Valencia (Kitenesi) variety exhibited the highest mean number of *D. citri* per tree, suggesting it is the preferred choice for the pest. Additionally, its commercial prominence in Tanzania further increases its exposure and accessibility to *D. citri*. On the other hand, the Bitijuma, Jaffa (Shamoti), Local varieties, Mediterranean (Nairobi), and Washington navel (Kitovu) varieties displayed zero *D. citri* counts per tree, suggesting potential resistance or repellence to the pest. The Matombo sweet and Valencia (Msasa) varieties exhibited low mean numbers of *D. citri* per tree, indicating a moderate level of susceptibility or attractiveness to the pest, possibly due to specific characteristics making them less favourable or accessible to *D. citri* than the Late Valencia (Kitenesi) variety. These findings hold significant implications for the management of Huanglongbing (HLB) and its vector in Tanzania and other citrus-producing regions in East Africa. One key strategy to bolster HLB control efforts is to reduce the population and activity of *D. citri* (Li *et al*., 2020). A promising avenue to pursue in this regard is the selection and cultivation of citrus varieties that display resistance to this pest, as proposed by Borgoni *et al*. in 2014. This research identified five citrus varieties that consistently show zero *D. citri* counts per tree. This discovery holds great promise for advancing HLB-resistant citrus breeding programs and integrated pest management practices in Tanzania and neighbouring East African countries (Table 6). These varieties can serve as valuable candidates for further investigation and development (Chen & Stelinski, 2017; Eduardo *et al*., 2022). Still, it's important to stress the need for more research to confirm whether these identified varieties are resistant or repellent to *D. citri* in a range of environmental conditions. Based on our research, we have found that the presence of new flushes greatly influences the occurrence and abundance of citrus psyllids. Specifically, citrus plants that exhibit moderate to high intensity of new flushes had a significantly higher number of *D. citri* per plant, as demonstrated in Figure 2.7. Similar studies were conducted by Tsai *et al*. (2002) and Hall *et al*. (2008), which showed that citrus psyllids abundance correlated with the intensity of new flushes. Adult psyllids are attracted to new flushes due to the yellowish color they produce (Wu *et al*., 2015). In addition, new flushes release volatile organic compounds (VOCs) that attract *D. citri* from a distance (Zhao *et al*., 2013). Therefore, *D. citri* has developed strategies to deal with the changing availability of new flushes. For example, during periods of low flush availability, *D. citri* enters a state of reproductive diapause (temporary cessation of reproduction) until new flushes appear, at which point they resume reproduction (Britt *et al*., 2020).

Table 4. Overview of successful measures for managing various pests and diseases, recommended for other parts of Africa cultivating citrus and fruit trees.

Management Practice	Description	Applicability in Africa
Biopesticides	Use of natural organisms like *Beauveria bassiana* and botanical pesticides (Ramírez-Godoy *et al.*, 2018).	Highly recommended due to environmental sustainability and effectiveness.
Biodiversity Management	Encouraging natural predators and functional biodiversity through organic farming practices (Rugno *et al*., 2021)	Suitable for organic orchards; promotes resistance to pest proliferation.
Cultural Practices	Includes sanitation, pruning, mulching, and weed management (Lucas, 2011).	Essential for integrated pest management; applicable across various regions.
Chemical Control	Judicious use of insecticides and mineral oils (Leong *et al*., 2022).	To be used cautiously; recommended in combination with other IPM strategies.
Biological Control	Utilization of natural enemies and biocontrol agents (Rugno *et al*., 2021).	Effective and environmentally friendly; encourages local biodiversity.
Quarantine Measures	Inspection and certification to prevent the spread of pests (Leong *et al*., 2022).	Critical for maintaining market access and preventing regional spread.
Integrated Pest Management (IPM)	Combination of various control measures for long-term sustainability (Leong *et al*., 2022).	Recommended as a holistic approach to pest management.

CONCLUSION

This research provides valuable insights into the geographical disparities and distribution patterns of *D. citri* and *T. erytreae* within Tanzania. Our study underscores the predominance of *D. citri* in the Tanga and Morogoro regions, with the Tanga region serving as a newly documented area of infestation. Conversely, *T. erytrae* is exclusively confined to the Arusha region. These observed variations in psyllid abundance across regions underscore the localized nature of these infestations and underscore the critical need for tailoring management strategies to the specific characteristics of each region (Table 4).

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