



Inventories of the Main Insect Pests of Stored Corn and Repellent and Insecticidal Effects of Sapwood and Heartwood Extracts from Wood Côte d'Ivoire against *Sitophilus zeamais* Motschulsky (Coleoptera, Curculionidae)

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Inventories of the Main Insect Pests of Stored Corn and Repellent and Insecticidal Effects of Sapwood and Heartwood Extracts from Wood Côte d'Ivoire against *Sitophilus zeamais* Motschulsky (Coleoptera, Curculionidae)

**Appolinaire Bley Bley-Atse ^{a,b*}, Armand Nahoulé Adja ^c,
Florence Bobelé Niamké ^a, Jean Louis Lepetit N'guessan ^a,
Hakim Abdel Aziz Ouatarra ^a,
N'Guessan Jean Claude Yao ^a, Mathias Danho ^c,
Augustin Amissa Adima ^a and Nadine Amusant ^d**

^a Laboratory of Industrial Processes and Synthesis of the Environment and New Energies, National Polytechnic Institute Félix Houphouët-Boigny, P.O. Box 1313 Yamoussoukro, Côte d'Ivoire.

^b Wood Sciences Laboratory, Department of Forestry and Environment, Higher School of Agronomic Sciences, University of Antananarivo, P.O. Box 175, Antananarivo 101, Madagascar, Côte d'Ivoire.

^c Laboratory of Entomology and Agricultural Zoology, Higher School of Agronomic, National Polytechnic Institute Félix Houphouët-Boigny, P.O. Box 1313 Yamoussoukro, Côte d'Ivoire.

^d CIRAD ED Department, UMR Ecofog, PO Box 701, 91310 Kourou Cedex, France.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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*Corresponding author: E-mail: appobleyatse@gmail.com, bley.bley-atse18@inphb.ci

Abstract

Background: Cereals play a central and important role globally in food security, nutrition and energy. *Sitophilus zeamais* Motschulsky is without doubt the most devastating insect pest of agricultural stocks and is resistant to synthetic chemical pesticides. The search for botanical products with low toxicity for the environment and for living beings has intensified considerably. Forestry operations produce large quantities of waste that remain under-exploited, posing a real environmental problem. Studies have shown that tropical tree species synthesis biomolecules in their heartwood that are responsible for their natural resistance and could be highly effective against insect pests.

Objectives: The aim of this study was firstly to carry out an inventory of insect pests on stored maize and secondly to assess the repellent and insecticidal activity of hydroalcoholic extracts of *Nauclea diderrichii*, *Mansonia altissima* and *Milicia excelsa* against *Sitophilus zeamais*.

Method: Stored maize samples were collected, insect pests were identified, and their relative abundance was calculated. Hydroalcoholic extracts of sapwood and heartwood were then tested, in comparison with a synthetic chemical insecticide, Protect DP (1.5% pyrimiphos-methyl and 0.1% deltamethrin), on *S. zeamais* to evaluate their insecticidal activity (mortality, LD₅₀, TL₅₀) and repellency at different concentrations, using a randomised experimental design with three replicates.

Results. The inventory showed that *S. zeamais* with a Relative Abundance (Ra) of 51.06% (Ra ≥ 10%) and *T. castanenum* with an Ra of 43.61% were abundant species. Hydroalcoholic extracts of sapwood from *N. diderrichii*, *M. altissima* and *M. excelsa* resulted in mortality rates of 80-96.67%, 76.67-88.33% and 66.67-81.67% respectively. The mortality of heartwood extracts from these same woods varied respectively from 58.33 to 95%, from 66.67 to 95% and from 36.67 to 78.33%. The LD₅₀ of sapwood extracts was between 0.0093 and 0.0289 and the TL₅₀ ranged from 3.5 to 6.2 days. The LD₅₀ of heartwood extracts was between 0.050 and 0.1435 g/mL and the TL₅₀ varied from 1.8 to 0.5 days. The repellency rate ranged from 26.67 to 96.67% after 1 hour and from 50 to 93.37% after 2 hours' exposure to the extracts tested.

Conclusions. The toxicity of the extracts is due to the presence of the main secondary compounds present in hydroalcoholic wood extracts. These results demonstrate the potential of wood extracts for controlling insect pests of stored foodstuffs.

Keywords: Wood extracts; repellent; insecticide; stock pests; Côte d'Ivoire.

1. Introduction

The increase in the world's population is leading to a high demand for food, and this is creating ever greater food insecurity. Cereal harvests represent several million tonnes and are unfortunately subject to the risk of infestation and continuous contamination by insect pests. As a result, more than 30% of losses are recorded in developing countries (Throne & Eubanks, 2002). This risk is most acute during post-harvest transport, storage, and processing in stored food production facilities. Stored foodstuffs are very important, as their purpose is to feed people and ensure the long-term survival of crops. They also ensure that future plantings and harvests are in place. That's why pests on stored products need to be carefully controlled. This control must be based on a sustainable approach to pest control

(Stejskal et al., 2015). The corn weevil, *Sitophilus zeamais*, is one of the most important insect pests of stocks. It can cause major weight loss in stored maize (20 to 90%) if left untreated (Gariba et al., 2021). It is a polyphagous insect, as it can also attack cereals, grains, flour and dry or powdered products. Chemical control is the most widely used method of combating stored food pests. However, this method has harmful effects on the environment and on human health (Hamel et al., 2020). That's why we urgently need to find sustainable, more environmentally-friendly alternatives (Shaaya & Kostjukovsky, 1998). Natural insecticides made from secondary plant substances should be more widely used as alternatives to synthetic pesticides (Isman & Tak, 2017). They have low toxicity for non-target organisms, and their mode of action is varied due to their phytochemical composition. The forestry

industry produces over 2 million m³ of sawdust a year worldwide (Cheah et al., 2013; Mwango & Kambole, 2019). Sawmills generate 40 to 60% of the solid waste resulting from the processing of logs (Souza et al., 2018). The failure to recover and manage this waste leads to serious health and environmental problems, such as air and water pollution, greenhouse gas emissions and the destruction of aquatic life (Cetiner & Shea, 2018; Mwango and Kambole, 2019). In addition, several studies have revealed that sustainable tropical species synthesise biomolecules in their wood that are responsible for their natural resistance, such as total phenols, tannins and flavonoids (Niamké et al., 2021). However, a large quantity of bioactive compounds (flavonoids, terpenes, eg.) present in certain tree branches, such as knots, are very often left behind when the wood is processed, and knots are richer in bioactive substances than the heartwood and sapwood of softwoods.

In addition, the sapwood rejected in most cases during wood processing may also contain non-structural carbohydrates, gums, resins, silicates, or extractives precursors. In fact, the synthesis of bioactive extractives in the sapwood, precursors of extractives stored in the heartwood during the duraminisation process, shows just how important the sapwood is in terms of molecules of interest (Taylor et al., 2002; Hillis, 2012; Lehnbach, 2015). It has also been shown that trees grown in forests are now more disturbed than trees previously studied in the literature. New bioactive defense molecules are likely to be synthesized in these trees. This bio-waste should be sufficiently recovered to solve the problem of poor waste management and the sustainable recovery of natural resources. Indeed, the recovery of forestry waste appears to be an opportunity to generate added value for forestry products in all countries, and more specifically for developing countries. Although certain biomolecules have been chemically characterized, there are few applications as biopesticides against crop pests. Given the functional properties of biomolecules, the extractives contained in forestry waste could be used as alternatives to synthetic chemical pesticides (Jurd & Manners, 2002; De Meeûs, 2019).

This study aims to develop a natural pesticide from wood waste to kill insects that destroy stored crops. This work is important because it transforms wood waste into useful agricultural

products, reducing pollution and the use of chemical pesticides while better protecting stored foodstuffs and the environment. This approach is part of a circular economy, emphasising the reuse of waste. Two types of wood were analysed: sapwood, which is generally discarded by the wood processing industry, and heartwood, which is valued by these industries.

For this reason, the present study aims to identify the main insect pests of maize stocks and to evaluate extracts from the three durable woods studied, namely Badi (*Nauclea diderrichii*), Bete (*Mansonia altissima*) and Iroko (*Milicia excelsa*), as potential biopesticides against *S. zeamais*. This article describes for the first time the insecticidal and repellent activity of sapwood and heartwood extracts against one of the most important pests of maize stocks, *S. zeamais*.

2. Materials and Methods

2.1 Material

2.1.1 Plant Material

The plant material consisted of maize seed of the variety EV8728-SR from an untreated experimental field planted between September and December 2020. The seeds were stored in polystyrene bags. The material also consisted of shredded sapwood and heartwood from three tropical forest species in Côte d'Ivoire: *N. diderrichii* (Badi), *M. altissima* (Bete) and *M. excelsa* (Iroko).

2.1.2 Chemical Material

Protect DP, a registered synthetic chemical insecticide for stored grain, consisting of deltamethrin 1 g/Kg and pirimiphos-methyl 15 g/Kg for the 50 g sachet, was used. 70° alcohol was used to prepare the positive control (water and ethanol).

2.1.3 Animal Material

The animal material consisted of 800 young adult *S. zeamais* insects of approximately one week of age. They were taken from rearing stocks kept in the laboratory (temperature 27 ± 2°C; relative humidity 70 ± 5% and a photoperiod of 12h of light and 12h of darkness) (Niber, 1994; Weaver et al., 1997; Tapondjou et al., 2005). The selected insects were starved and used for the biological tests.

2.2 Methods

2.2.1 Insect Identification and Inventory

The insects found on the stock were collected using sieves (25 mm and 50 mm) and containers. Identification was carried out by observing the morphological characteristics (head, abdomen, thorax, colour) of the insects using a MOTIC binocular magnifying glass (G×50) and an LCD Digital electronic microscope (500×Zoom). Online identification keys and physical keys (books) were also used (Cruz et al., 2016). Insects that exhibited lively, voracious, and agile behaviour were considered suitable for the study. Relative abundance (Ra) was calculated according to Zaime and Gautier, (1989) and Tra-Bi et al. (2014). Ra is the ratio between the number of individuals of a species (Ni) taken into consideration and the total number of individuals (N) of all species combined. Ar and Ni were determined for each species. Table 1 shows the four classes of Ra:

$$Ra (\%) = \frac{Ni}{N} \times 100$$

Ni : abundance ; Ra : Relative abundance.

2.2.2 Repellent Effect of Hydroethanolic Wood Extracts on Filter Paper

The repellent or insect repellent effect of the extracts on the insects used in the experiment was evaluated using the filter paper preference zone method. This method was described by McDonald et al. (1970). Filter paper discs with a diameter of 9 cm were cut into two equal parts, each with a surface area of 31.81 cm². Four doses of extracts were prepared separately (1, 2.5, 5 and 10 µL) by diluting these extracts in 1 mL of hydroethanolic solvent. Each of the half-discs, with a diameter of 4.5 cm, received 0.5 mL of the prepared extract.

Each extract obtained was spread evenly over half of the disc. The respective and corresponding doses were as follows: 0.031; 0.079; 0.157 and 0.314 µL/cm². In contrast, the other half received only 0.5 mL of the hydroethanolic solvent (alcohol + water). The treated half-discs were then exposed for 15 minutes to facilitate evaporation of the dilution solvent (alcohol).

Afterwards, the two halves of each disc, each with a surface area of 31.81 cm², were reattached using adhesive tape (thickness = 1.8 cm). The reconstituted filter paper disc was placed in a Petri dish. A batch of 20 adult insects, aged no more than two weeks, was placed in the center of each disc, precisely on the adhesive tape. Four replicates were performed for each dose (Fig. 1). The number of insects present on the part of the paper treated with the hydroethanolic wood extract (Nex) and the number of insects present on the part treated only with the solvent (alcohol+ water: Nae) were recorded after 1 hour and after 2 hours. The repellency rate (RR) was calculated using the following formula:

$$RR = \frac{(Nae - Nex)}{(Nex - Nae)} \times 100$$

Nex: Number of insects present on the part of the paper treated with hydroethanol extract of wood;

Naw: Number of insects present on the part treated solely with solvent (alcohol+ water);

RR: repellency rate (%).

After determining the average repellency percentage of each hydroethanolic wood extract, a classification was established based on the different repellency classes defined by McDonald et al. (1970). Six classes ranging from 0 to V were defined. Different repellency classes are listed in Table 2.

Table 1. Classification of the Ra according to Adja et al. (2014)

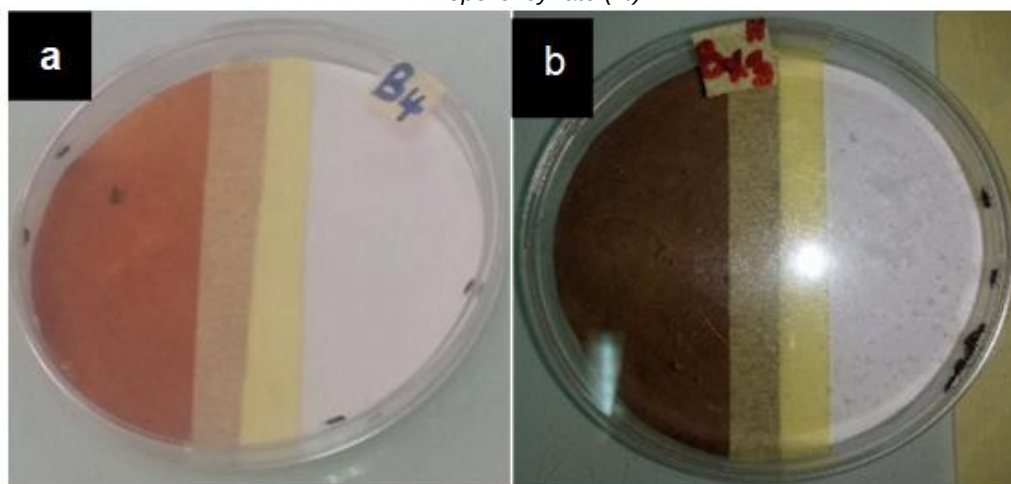
Classes	Relative Abundance (Ra)	Interpretation
I	Ra less than 1%	Species not very abundant
II	Ra between 1 and 5%	Fairly abundant species
III	Ra between 5 and 10%	Abundant species
IV	Ra greater than or equal to 10%	Very abundant species

Ra: Relative abundance

Table 2. Classes of repulsion rates according to McDonald et al. (1970) adapted by Viglianco et al. (2008)

Classes	Repulsion rate (RR)	Interpretation
0	RR less than 0.1%.	No repulsion
I	RR between 0.1 and 20%.	Low repulsion
II	RR between 20.1% and 40%.	Low to mediocre repulsion
III	RR between 40.1% and 60%.	Medium to good repellency
IV	RR between 60.1% and 80%.	Good to strong repulsion
V	RR between 80.1% and 100%.	Strong to complete repulsion

RR: repellency rate (%)

**Fig. 1. Repellent effect of wood extracts tested on filter paper against *Sitophilus zeamais***
(a) Extract of Badi wood (*Nauclea diderrichi*); (b) Badi wood extract (*Mansonia altissima*)

2.2.3 Insecticidal Effect of Hydroethanol Extracts of Wood on Filter Paper

Four doses were prepared. Each of the prepared solutions was spread evenly on a 9 cm diameter filter paper disc (Whatman No. 1) placed at the bottom of a Petri dish of the same diameter. This equates to a surface area of 63.617 cm² (Obeng-Ofori et al., 1997; Ojimelukwe & Adler, 1999; Tapondjou et al., 2005). The discs were exposed to the open air for 15 minutes to facilitate evaporation of the dilution solvent. This corresponds to respective doses of 0.08 µL/cm², 0.16 µL/cm², 0.24 µL/cm² and 0.31 µL/cm² per unit area of filter paper. The fifth batch received only the chemical treatment, while the sixth batch (control batch) was treated only with ethanol + water solvent (V/V: 2 mL/2 mL). A batch of 20 young adult insects freshly collected from their breeding environment was introduced into each Petri dish containing a treated disc (filter paper). The dishes were then immediately closed. Three replicates were performed for each of the respective doses and the dead insects, kept in the Petri dish, were counted every 24 hours. This counting was carried out over 10 days. Mortality

in the treated boxes (Mo) was expressed as adjusted mortality (Ma). This took into account the natural mortality observed in the control Petri dishes (Mn) according to Abbott (1925), reported and adapted by Ileke (2014) :

$$Ma = \frac{(Mo - Mn)}{(100 - Mn)} \times 100$$

Ma: Adjusted mortality.

Mo: Mortality observed in petri dishes treated with wood extracts.

Mn: Natural mortality observed in control petri dishes.

Finney's method, based on the regression of mortality probit values against the logarithms of different extract doses, made it possible to determine two other parameters (Finney, 1978): The LD₅₀ or lethal dose 50 is the dose of product capable of causing 50% mortality within 24 hours (Ruiz et al., 2008). The LT₅₀ or lethal time 50 is the time after which 50% of insects die following the application of different products (Fig. 2).

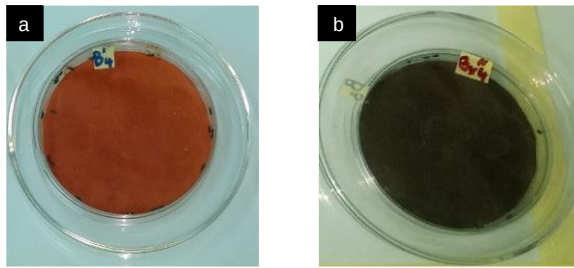


Fig. 2. Insecticidal evaluation of wood extracts tested on filter paper against *S. zeamais*

(a) Extract of Badi wood (*Nauclea diderrichi*); (b) Badi wood extract (*Mansonia altissima*)

These parameters were determined to evaluate the effectiveness of the treatments applied (Ruiz et al., 2008).

2.2.4 Data Analysis

The data were analysed using XLSTAT 2023 1.2 (version 1406) for the analysis of variance (ANOVA). The non-parametric Kruskal-Wallis test was used after the normality test was negative. A multiple comparison analysis using Dunn's test was used to compare the mortality and repulsion rates at the 5% probability threshold.

3. Results

3.1 Inventory of Insects Collected on Maize Grains

Ten species were recorded. They belonged to two major orders: Coleoptera and Lepidoptera. Among the Coleoptera, there are primary pests

such as *Sitophilus zeamais*, *Prostephanus truncatus*, *Dinoderus bifoveolatus* and secondary pests such as *Tribolium confusum*, *Palorus subdepressus*, *Tribolium castenum*, *Carpophilus hemipterus*. Lepidopteran pests included *Ephestia cautella*, *Plodia interpunctella*, *Sitotroga cerealella* and Gelechiidae. *S. zeamais* caused the most damage to grain. The species *S. zeamais* with a Ra of 51.06% ($Ra \geq 10\%$) and *T. castenum* with an Ra of 43.61% were considered as abundant species. *T. confusum* with a Ra of 2.03 ($1 \leq Ra < 5\%$) and *Sitotroga cerealella* with an Ra of 1.32 ($1 \leq Ra < 5\%$) were considered abundant species. Seven other species such as *P. truncatus*, *D. bifoveolatus*, *P. subdepressus*, *C. hemipterus*, *E. cautella*, *P. interpunctella* and *S. cerealella* with an Ra of less than 1 ($Ra < 1\%$) were considered as low abundance species (Table 3).

3.2 Insecticidal Effect of Sapwood and Heartwood Extracts against *Sitophilus zeamais*

The mortality rate after exposure to the different wood extracts assessed is shown in Fig. 3. The mortality rate was zero in the untreated control. In contrast, the reference control, the chemical insecticide Protect DP, caused 100% insect mortality on day 2 (Fig. 3a and 3a'). The alcohol control caused a very low mortality rate of 3.33% on day 8.

At a concentration of $0.08\mu\text{L}/\text{cm}^2$, heartwood extracts were significantly ($p < 0.05$) more active than sapwood extracts. The heartwood extracts recorded a more rapid mortality rate over time (from day 1) than the sapwood extracts.

Table 3. Inventory and abundance of insect pests observed in stocks

Orders	Families	Scientific name	Pest status	Population (P)	Ra (%)
Coleoptera	Curculionidae	<i>Sitophilus zeamais</i>	Primary	5539	51,060
	Bostrichidae	<i>Prostephanus truncatus</i>	Primary	15	0,138
	Bostrichidae	<i>Dinoderus bifoveolatus</i>	Primary	80	0,737
	Tenebrionidae	<i>Tribolium castenum</i>	Secondary	4731	43,612
	Tenebrionidae	<i>Tribolium confusum</i>	Secondary	221	2,0372
	Tenebrionidae	<i>Palorus subdepressus</i>	Secondary	23	0,2120
	Nitidulidae	<i>Carpophilus hemipterus</i>	Secondary	19	0,1751
Lepidoptera	Gelechiidae	<i>Sitotroga cerealella</i>	Primary	143	1,3182
	Lepidoptera	<i>Ephestia cautella</i>	Primary	40	0,3687
	Lepidoptera	<i>Plodia interpunctella</i>	Secondary	37	0,3411
Total				10748	100

Legend: Ra: Relative abundance (%)

Table 4. Toxicity of sapwood extracts at day 7

Extract	Scientific name	Concentration ($\mu\text{L}/\text{cm}^2$)	Mortality (%)	Mortality (probit unit)	LT ₅₀ (days)	LD ₅₀ ($\mu\text{L}/\text{cm}^2$)	R ²
Badi Sapwood	<i>N. diderrichii</i> (Rubiaceae)	0.08	80	5.84	5.5	0.0289	0.8556
		0.16	85	6.04	5.4		
		0.24	91.67	6.41	4.6		
		0.31	96.67	6.88	4.4		
Bété Sapwood	<i>M. altissima</i> (Malvaceae)	0.08	76.67	5.74	5.5	0.0093	0.9764
		0.16	81.67	5.92	5.3		
		0.24	86.67	6.13	4.5		
		0.31	88.33	6.18	4.4		
Iroko Sapwood	<i>M. excelsa</i> (Moraceae)	0.08	66.67	5.44	6.2	0.0283	0.8101
		0.16	68.33	5.47	6.2		
		0.24	78.33	5.77	5.7		
		0.31	81.67	5.95	3.5		

Table 5. Toxicity of heartwood extracts on day 2

Extract	Scientific name	Concentration ($\mu\text{L}/\text{cm}^2$)	Mortality (%)	Mortality (probit unit)	LT ₅₀ (Days)	LD ₅₀ ($\mu\text{L}/\text{cm}^2$)	R ²
Badi Heartwood	<i>N. diderrichii</i> (Rubiaceae)	0.08	58.33	5.20	1.7	0.0706	0.9652
		0.16	76.67	5.74	0.9		
		0.24	93.33	6.48	0.5		
		0.31	95	6.64	0.5		
Bete Heartwood	<i>M. altissima</i> (Malvaceae)	0.08	66.67	5.44	0.7	0.0550	0.8654
		0.16	75	5.67	0.6		
		0.24	78.33	6.13	0.5		
		0.31	95	6.64	0.5		
Iroko Heartwood	<i>M. excelsa</i> (Moraceae)	0.08	36.67	4.67	1.8	0.1435	0.8478
		0.16	58.33	5.20	1.1		
		0.24	68.33	5.47	0.6		
		0.31	78.33	5.77	0.5		

Legend: LT₅₀: Lethal time at which 50% of insect mortality is observed; LD₅₀: Lethal dose kills 50% of insects;
R²: Coefficient of determination.

On the other hand, sapwood extracts had a mortality rate of between 83.33 and 90% from day 8. Bete heartwood ($96.67 \pm 1.15\%$) and Iroko heartwood ($86.67 \pm 6.65\%$) were the most active, followed by Badi ($73.67 \pm 4.04\%$). Mortality was estimated at over 80% for the three heartwood extracts from day 6.

When the concentrations were doubled ($0.16 \mu\text{L}/\text{cm}^2$), a similar mortality was observed. In fact, heartwood extracts were significantly ($p < 0.05$) more active than sapwood extracts. Also, the mortality rate induced by the heartwood extracts was relatively faster over time than that of the sapwood extracts. The three sapwood extracts from Bete and Badi caused mortality between 58.33 ± 2.52 and $91.67 \pm 6.03\%$ between day 6 and day 8. Heartwood extract from Badi ($98.33 \pm 2.89\%$) and Iroko ($95 \pm 3.46\%$) had the best activity, followed by Bete ($86.67 \pm 6.5\%$). The heartwood extracts had almost the same effect as the synthetic chemical Protect DP, eliminating almost all the insects (Fig. 3b and 3b').

The heartwood extracts were significantly ($p < 0.05$) more active than the sapwood extracts once the concentrations ($0.24 \mu\text{L}/\text{cm}^2$) were tripled. In addition, a relatively slower rate of mortality was observed in the sapwood than in the duramen. Sapwood extracts had a low mortality of between 6.67 ± 2.08 and 93.33% between days 4 and 8. In terms of sapwood, Bete and Iroko extracts had almost the same activity with $1.67 \pm 0.58\%$ deaths from day 1 to day 3. The mortality rate increased from day 4 to day 8 for the three sapwood extracts, with mortality rates ranging from 25 ± 3.61 and $93.33 \pm 5.03\%$ for Badi, 21.66 ± 2.08 and $93.33 \pm 7.23\%$ for Bete and 6.67 ± 2.31 and $80 \pm 3.61\%$ for Iroko. The mortality rate was $100 \pm 0\%$ for heartwood extracts from Badi (day 4) and Bete (day 7). The synthetic pesticide Protect DP caused similar insecticidal activity with $100 \pm 0\%$ mortality on day 2. However, the response time was shorter for Badi and Bete heartwood extracts (day 4 and 7) (Fig. 3c and 3c').

At a concentration of $0.31 \mu\text{L}/\text{cm}^2$, sapwood extracts were not significantly ($p > 0.05$) more active than heartwood extracts. However, a similar insecticidal effect was observed between the synthetic chemical Protect DP and the extracts of duramen from Badi, Bété and Iroko. The sapwood extracts caused a mortality rate of between 5 ± 1 and $100 \pm 0\%$ between day 4 and day 8. Badi extract ($21.66 \pm$

3.21 to $100 \pm 0\%$) was more effective than Bete extract (5 ± 1 to 95 ± 3.46) and Iroko extract (51.67 ± 4.04 to $93.33 \pm 5.03\%$) during the same time interval. The synthetic chemical pesticide Protect DP caused similar insecticidal activity to the Badi and Bete heartwood extracts, eliminating $100 \pm 0\%$ on day 2 (Fig. 3d and 3d').

The LD_{50} of Badi, Bete and Iroko sapwood extracts were 0.0289 , 0.0094 and $0.0283 \mu\text{L}/\text{cm}^2$ respectively on day 7, while the LD_{50} of Badi, Bete and Iroko duramen extracts were 0.0706 , 0.055 and $0.1435 \mu\text{L}/\text{cm}^2$ respectively on day 2. The LT_{50} determined for the different doses applied varied. It was longer for sapwood extracts (3.5 to 6.2 days) and shorter for heartwood extracts (0.5 to 3.4 days). The LT_{50} for duramen extracts was almost similar to that for Protect DP, which was 0.5 days. Thus, for sapwood doses of $0.08 \mu\text{L}/\text{cm}^2$, the LT_{50} was 5.5 days for Badi, 5.5 days for Bete and 6.2 days for Iroko. LT_{50} was 5.4 days for Badi, 5.3 days for Bete and 6.2 days for Iroko for sapwood doses of $0.16 \mu\text{L}/\text{cm}^2$. In addition, for sapwood doses of $0.24 \mu\text{L}/\text{cm}^2$, the LT_{50} was 4.6 days for Badi, 4.5 days for Bete and 5.7 days for Iroko. For sapwood doses of $0.31 \mu\text{L}/\text{cm}^2$, the LT_{50} were 4.4 days for Badi and Bete and 3.5 days for Iroko.

For heartwood extract doses of $0.08 \mu\text{L}/\text{cm}^2$, the LT_{50} was 1.7 days for Badi, 0.7 days for Bete and 1.8 days for Iroko. For doses of $0.16 \mu\text{L}/\text{cm}^2$, the LT_{50} was 0.9 days for Badi, 0.6 days for Bete and 1.1 days for Iroko. For doses of $0.24 \mu\text{L}/\text{cm}^2$, the LT_{50} was 0.5 days for Badi, 0.5 days for Bete and 0.6 days for Iroko. For heartwood doses of $0.31 \mu\text{L}/\text{cm}^2$, the LT_{50} was 0.5 days for Badi, 0.5 days for Bete and 0.5 days for Iroko. LD_{50} were determined from logistic regression of probit units (Tables 4 and 5).

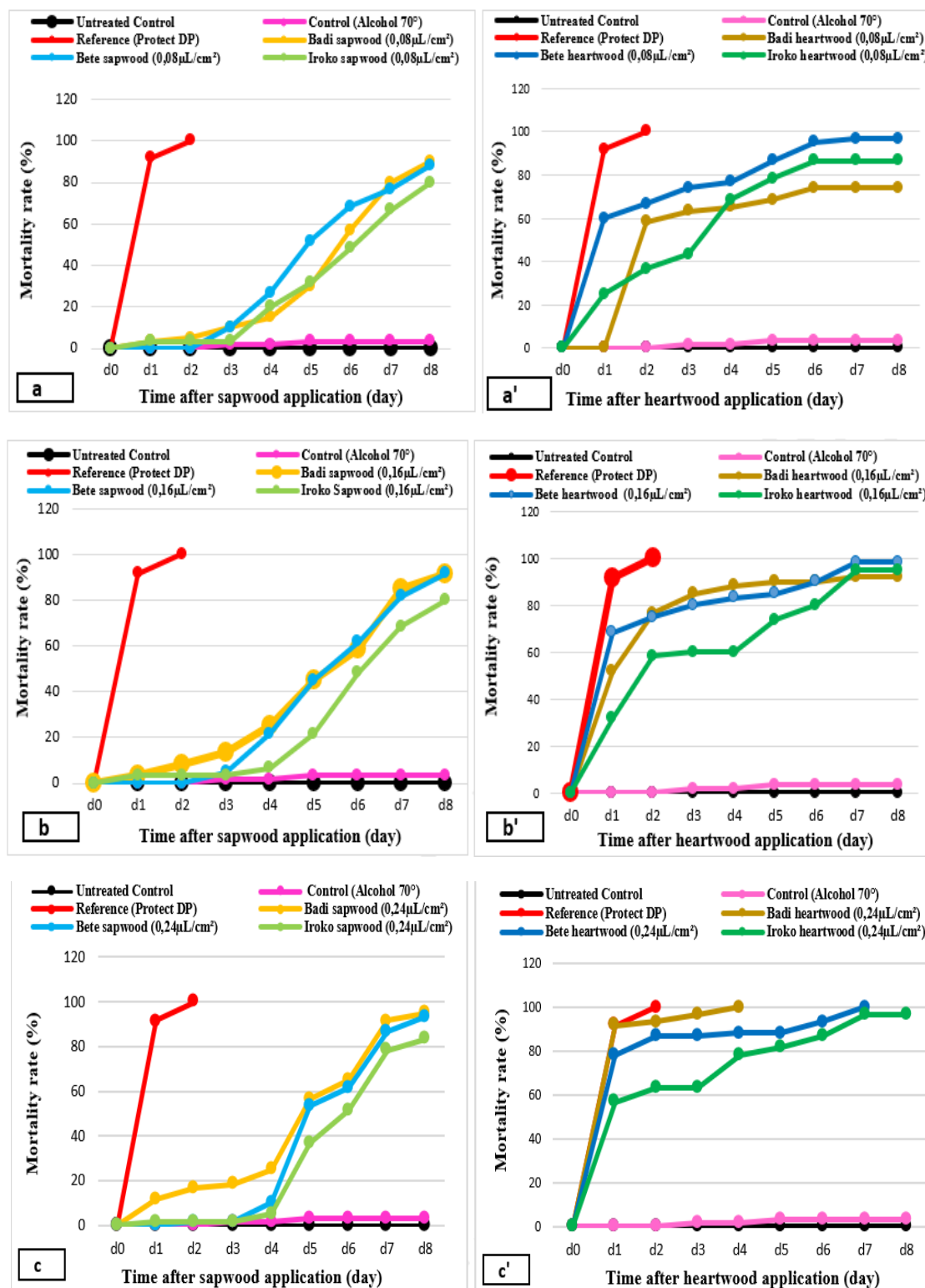
3.3 Repellent Effect of Wood Extracts on *Sitophilus zeamais*

3.3.1 Repellent Effect of Sapwood Extracts against *Sitophilus zeamais*

At a dose of $C_1 = 0.031 \mu\text{L}/\text{cm}^2$, there was a significant difference after 1 hour ($p < 0.05$; $p = 0.0243$) and after 2 hours of exposure to the extracts ($p < 0.05$; $p = 0.0156$) between the repellency rate of the sapwood extracts studied and the T_{twa} control (70° alcohol). The alcohol control showed a low repulsion rate after 1 h of

exposure time ($RR_1 = 26.67 \pm 2.31\%$) and a high repulsion rate after 2 h of exposure time ($RR_2 = 20 \pm 3\%$). The repulsion rate was low for Badi sapwood extract with a RR_1 of $26.67 \pm 3.06\%$ and a RR_2 of $50 \pm 2.65\%$. Iroko sapwood extract

showed strong to moderate repellency with a RR_1 of $70 \pm 4\%$ and a RR_2 of $60 \pm 4.58\%$. Bete sapwood extract had the best repulsion rate with a $RR_1 = 96.67 \pm 1.52\%$ and $RR_2 = 80 \pm 2.65\%$ (Table 6).



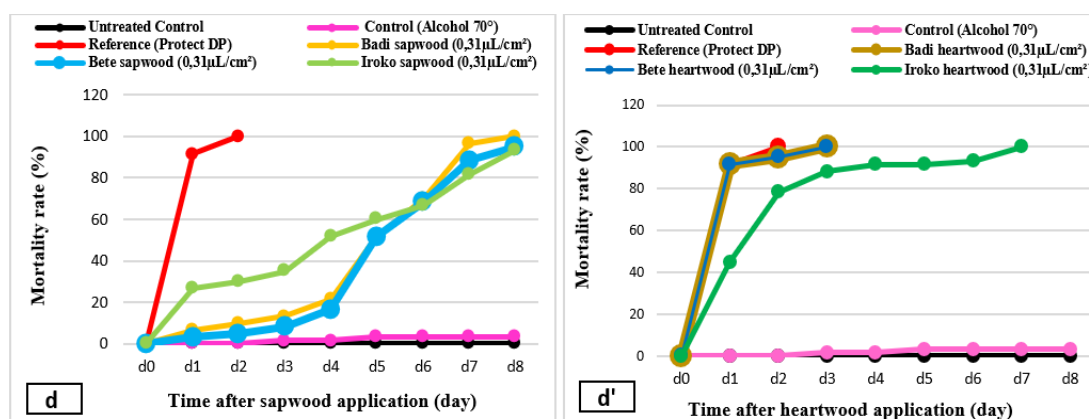


Fig. 3. Mortality rate of *S. zeamais* at different doses

[(a & a') $C_1 = 0.24$, (b & b') $C_2 = 0.08$, (c & c') $C_3 = 0.16$ and (d & d') $C_4 = 0.31 \mu\text{L}/\text{cm}^2$]

When the concentration was doubled ($C_2 = 0.0791 \mu\text{L}/\text{cm}^2$), a significant difference was observed after 1 h ($p=0.0239$) and after 2 h ($p=0.0185$) between the repulsion rate of the extract of Bété, Badi and Iroko sapwood and the T_{twa} control (alcohol). Iroko sapwood extract caused good repellency after 1 h ($RR_1 = 69.33 \pm 3.05\%$) and after 2 h ($RR_2 = 66.67 \pm 3.06\%$). Bete sapwood extract gave the best repulsion rate after 1 h ($RR_1 = 96.67 \pm 1.15\%$) and 2 h ($RR_2 = 86.67 \pm 6.51\%$).

When the concentration was tripled ($C_3 = 0.157 \mu\text{L}/\text{cm}^2$), a significant difference was observed 1 h later ($p=0.0210$) and 2 h later ($p=0.0153$) between the repellency rate of Bete sapwood extract and that of Badi sapwood extract, Iroko sapwood extract and the control (alcohol). The repellency rate was lowest for Iroko sapwood extract with a RR_1 of $63.33 \pm 3.06\%$ and a RR_2 of $60 \pm 3.61\%$. Badi sapwood extract had a good repellency with a RR_1 of $83.37 \pm 2.89\%$ and a high RR_2 of $80 \pm 3.61\%$. Bete sapwood extract caused the best repulsion through a very strong repulsion with a RR_1 of $86.67 \pm 4.93\%$ and a RR_2 of $93.37 \pm 1.15\%$ (Table 6).

At the highest dose ($C_4 = 0.314 \mu\text{L}/\text{cm}^2$), there was a significant difference between the repellency rate of the three sapwood extracts tested and the T_{twa} control (alcohol control) after 1 h ($p<0.0001$) and after 2 h ($p=0.0172$). There was also no significant difference between the repellent action of Badi sapwood and Iroko. Badi sapwood extract had a good repellency rate with a RR_1 of $83.33 \pm 4.16\%$ and a RR_2 of $83.67 \pm 4.16\%$. Bete extract had a very strong repulsion with a $RR_1 = 96.67 \pm 1.15\%$ and a RR_2 of $90 \pm 0\%$ (Table 6).

3.3.2 Repellent Effect of Heartwood Extracts against *Sitophilus zeamais*

At the lowest dose ($C_1 = 0.031 \mu\text{L}/\text{cm}^2$), there was a significant difference between the repellency rate of the heartwood extracts and the control (alcohol) after 1 hour ($p<0.05$; $p=0.0151$) and after 2 hours ($p<0.05$; $p=0.0166$). Iroko heartwood extract caused a strong repulsion with a RR_1 of 70 ± 4.58 and a RR_2 of $60 \pm 4.36\%$. Bete sapwood extract had the highest rate of repulsion with a RR_1 of $96.67 \pm 0.58\%$ and a RR_2 of $93.33 \pm 2.89\%$ (Table 7).

When the concentration was doubled ($C_2 = 0.0791 \mu\text{L}/\text{cm}^2$), there was a significant difference between the repellent activity of the heartwood extracts tested and that of the control (alcohol) after 1 hour ($p=0.0148$) and after 2 hours ($p=0.0153$) of exposure. The Badi heartwood extract had a high repulsion rate with a RR_1 of $90 \pm 1.73\%$ and a RR_2 of $83.33 \pm 5.77\%$. Iroko heartwood extract had a RR_1 of $63.33 \pm 5.78\%$ and a RR_2 of $73.33 \pm 3.51\%$. Bete heartwood extract had the best activity with a very high RR_1 of $93.33 \pm 1.52\%$ and a RR_2 of $90 \pm 1.73\%$ (Table 7).

When the concentration was tripled ($C_3 = 0.157 \mu\text{L}/\text{cm}^2$), a significant difference was observed between the repulsion rate of the extracts of all the duramen tested and that of the T_{twa} control (alcohol) after 1 hour ($p=0.0151$) and after 2 hours ($p=0.0155$). The Badi heartwood extract had a high repulsion rate ($RR_1 = 93.33 \pm 2.31\%$; $RR_2 = 93.33 \pm 1.15\%$). Bete heartwood extract had the best repulsion rate with a RR_1 of $76.67 \pm 2.08\%$ and a RR_2 of $98.33 \pm 1.15\%$ (Table 7).

Table 6. Repellent activity of sapwood extracts observed after 1 and 2 hours of exposure

Concentration ($\mu\text{L}/\text{cm}^2$) Time (Hour)	Repellency rate of sapwood extracts (%)							
	Alcohol control		Badi sapwood		Bete sapwood		Iroko sapwood	
	1 hour	2 hours	1 hour	2 hours	1 hour	2 hours	1 hour	2 hours
0,031 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	26.67 $\pm$ 3.06	50.0 $\pm$ 2.65	96.67 $\pm$ 1.52	80.0 $\pm$ 2.65	70.0 $\pm$ 4	60.0 $\pm$ 4.58
0,079 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	63.33 $\pm$ 3.5	80.0 $\pm$ 3.46	96.67 $\pm$ 1.15	86.67 $\pm$ 6.51	69.33 $\pm$ 3.05	66.67 $\pm$ 3.06
0,157 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	83.37 $\pm$ 2.89	80.0 $\pm$ 3.61	86.67 $\pm$ 4.93	93.37 $\pm$ 1.15	63.33 $\pm$ 3.06	60.0 $\pm$ 3.61
0,314 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	83.33 $\pm$ 4.16	83.67 $\pm$ 4.16	96.67 $\pm$ 1.15	90.0 $\pm$ 0.0	73.33 $\pm$ 2.89	70.0 $\pm$ 2.0

Table 7. Repellent activity of heartwood extracts observed after 1 and 2 hours

Concentration ($\mu\text{L}/\text{cm}^2$) Times (hour)	Repellency rate of heartwood extracts (%)							
	Alcohol control		Badi heartwood		Bete heartwood		Iroko heartwood	
	1 hour	2 hours	1 hour	2 hours	1 hour	2 hours	1 hour	2 hours
0,031 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	33.33 $\pm$ 4.51	53.44 $\pm$ 3.21	96.67 $\pm$ 0.58	93.33 $\pm$ 2.89	70.0 $\pm$ 4.58	60.0 $\pm$ 4.36
0,079 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	90.0 $\pm$ 1.73	83.33 $\pm$ 5.77	93.33 $\pm$ 1.52	90.0 $\pm$ 1.73	63.33 $\pm$ 5.78	73.33 $\pm$ 3.51
0,157 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	93.33 $\pm$ 2.31	93.33 $\pm$ 1.15	76.67 $\pm$ 2.08	98.33 $\pm$ 1.15	66.67 $\pm$ 4.16	66.67 $\pm$ 4.93
0,314 ($\mu\text{L}/\text{cm}^2$)	26.67 $\pm$ 2.31	20.0 $\pm$ 3.0	86.67 $\pm$ 2.89	86.67 $\pm$ 4.16	76.67 $\pm$ 5.69	98.34 $\pm$ 0.58	70.0 $\pm$ 2.0	73.33 $\pm$ 4.16

At the highest concentration ($C_4 = 0.314 \mu\text{L}/\text{cm}^2$), there was a significant difference between the repulsion rate of the duramen extracts and the Tt_{wa} (alcohol) control after 1 hour ($p=0.0218$) and after 2 hours ($p=0.0153$). The Badi heartwood extract had a RR_1 of $86.67 \pm 2.89\%$ and a RR_2 of $86.67 \pm 4.16\%$. Iroko heartwood extract showed good repellency with a RR_1 of $70 \pm 2\%$ and a RR_2 of $73.33 \pm 4.16\%$. Bete heartwood extract had the best repulsion rate with a RR_1 of $76.67 \pm 5.69\%$ and a RR_2 of $98.34 \pm 0.58\%$ (Table 7).

4. Discussion

The control and management of insect pests is a major concern for food processing companies. Infestation or even contamination of products can have serious economic consequences, which can be direct. These consequences can take the form of damage through deterioration in the quality of preserved or processed foods. They can also result in intangible losses due to customer and consumer dissatisfaction (Arthur & Phillips, 2002).

The results of this study show that the insects in stocks that attacked the stored maize belong to two orders, namely Coleoptera, which are the most numerous, and Lepidoptera. Although they were not found in this study, other orders such as Hymenoptera, Dictyoptera and Protoptera can also be found in stored commodities such as maize. Some are known as primary pests because they attack whole seeds. These include *Sitophilus zeamais*, *Prostephanus truncatus*, *Sitotroga cerealella* and *Ephestia cautella*. Another group of pests were described as secondary pests, because they attacked seeds that were already infested and damaged. In the course of this work, *Sitophilus zeamais* had a high frequency and a large population (5,539 individuals, or 51.09%) compared with the other insect pests listed. It was followed by *Tribolium castaneum* (43.61%). In addition, its relative abundance was the highest (51.06%).

Previous research has reported that these insects can attack and infest crops from the planting stage. This study has also confirmed this, especially as *Sitophilus zeamais* was found during the cob maturation phase of maize during an experiment carried out in a plantation in Yamoussoukro, Côte d'Ivoire, in 2020. These infestations can continue in the shop, at home or during transport. Most of these pests are cosmopolitan and know no borders. They can also be found in various stored products (seeds,

beans, flour, dried fruit) and in food processing facilities (Ngamo & Hance, 2007; Stejskal et al., 2015).

In general, the different concentrations of heartwood extracts evaluated ($0.031 \mu\text{L}/\text{cm}^2$; $0.079 \mu\text{L}/\text{cm}^2$; $0.157 \mu\text{L}/\text{cm}^2$ and $0.314 \mu\text{L}/\text{cm}^2$) were more effective in terms of repellent activity than sapwood extracts. The Bete extract was the most active, followed by Badi and Iroko. The activity of the sapwood extracts was still significant with the Iroko and Bete extracts. Indeed, at the lowest dose ($0.031 \mu\text{L}/\text{cm}^2$), they showed a good repellency rate after 1 hour and 2 hours with $70 \pm 4\%$ and $60 \pm 4.58\%$, respectively. A significant difference was observed between Bete heartwood extracts and Badi and Iroko extracts ($RR_{1h}=76.67 \pm 2.08\%$ and $RR_{2h}=98.33 \pm 2.31\%$). These results are thought to be due to the presence of repellent molecules in the extracts evaluated, particularly terpenes. The results showed that the repellent effect was dose-dependent, as the repellency rate (RR) increased with the dose of extract. These results are consistent with those of Tapondjou et al. (2005).

These authors showed significant repellent and toxic activity by contact with essential oils of *Eucalyptus saligna* and *Cupressus sempervirens* leaves against *Sitophilus zeamais* ($LD_{50}=0.36 \text{ mL}/\text{cm}^2$; $LD_{50}=38.05 \text{ mL}/40 \text{ g}$ of kernels) and *Tribolium confusum* ($LD_{50}=0.48 \text{ mL}/\text{cm}^2$). Impregnation of the filter paper discs and coating of the maize kernels with these oils resulted in a considerable reduction in insect reproduction and a reduction in kernel weight loss Tapondjou et al., 2005.

In addition, Wang et al., 2006 demonstrated significant repellent and toxic activity of *Artemisia vulgaris* essential oil against *T. castaneum* on filter paper at a dose of $0.6 \mu\text{L}/\text{mL}$ (v/v). A mortality rate of 100% was observed after four days of exposure (Wang et al., 2006). The wood extracts in this study showed greater overall efficacy than the essential oils evaluated by Wang et al. (2006), as the efficacy of these woods was observed after only 24 hours. In addition, Neiro et al. revealed in 2009 the toxicity of oxygenated monoterpenes and phenolic compounds in eucalyptus oil against *Sitophilus zeamais* and *Tribolium confusum* with LD_{50} values of $0.36 \mu\text{L}/\text{cm}^2$ and $0.48 \mu\text{L}/\text{cm}^2$. Previous studies have shown that monoterpenoids, especially those derived from aromatic plants such as *Apium graveolens*, *Juniperus oxycedrus*,

and *Citrus sinensis*, possess ovicidal, repellent, fumigant, and contact toxicity properties (Prates et al., 1998; Papachristos & Stamopoulos, 2002). Nerio et al., 2009 also demonstrated the repellent activity of oil extracted from *Eucalyptus citriodora* and *Tagetes lucida* at doses ranging from 0.063 to 0.503 $\mu\text{L}/\text{cm}^2$. Admittedly, these researchers tested essential oils, but their active doses are much higher than the highest dose of wood extract evaluated in this study (0.314 $\mu\text{L}/\text{cm}^2$). In the case of the 70° alcohol fraction, the low insect mortality throughout the experiment also suggested that the 70° fraction was probably not toxic to insects. The low mortality caused by the 70° fraction justifies its choice as the solvent for assessing the toxicity of the extracts in this study.

The mortality rate was zero in the untreated control due to the absence of treatment. In contrast, the insecticide reference control (Protect DP) caused the death of all insects on day 2 (100%). This mortality was due to two molecules, pyrimiphos-methyl 1.5% and deltamethrin 0.1%. Pyrimiphos-methyl, a member of the organophosphate family, acts by inhibiting acetylcholinesterase. This substance is the essential enzyme that regulates nerve impulses at junctions in the insect nervous system. It acts by contact, ingestion and inhalation. Deltamethrin is a chemical compound in the pyrethroid family. It is used as an insecticide and insect repellent because of its neurotoxic properties. However, even though these products eliminate insects, we have to recognise that they are harmful to human health and the environment (Gandaho et al., 2020).

The LD_{50} for sapwood from Badi, Bete and Iroko were 0.0289, 0.0093 and 0.0283 $\mu\text{L}/\text{cm}^2$ respectively, while the LD_{50} for heartwood from Badi, Bete and Iroko were 0.0706, 0.0550 and 0.1435 $\mu\text{L}/\text{cm}^2$ respectively. The heartwood extracts from Bete, Badi and Iroko at the different concentrations evaluated (0.08 $\mu\text{L}/\text{cm}^2$; 0.16 $\mu\text{L}/\text{cm}^2$; 0.24 $\mu\text{L}/\text{cm}^2$; 0.31 $\mu\text{L}/\text{cm}^2$) caused a higher mortality rate and a shorter lethal time 50 (LT_{50}) than those from sapwood. These results are probably due to the dose (dose-dependent effect) and the high content of secondary metabolites in heartwood compared with sapwood. These secondary metabolites would have acted either by contact or inhalation. The most plausible action is the neurotoxicity of the extracts. Alkaloids, polyphenols, flavonoids, tannins and terpenes have already demonstrated their insecticidal potential in scientific studies

(Ileke, 2014; Loko et al., 2017; Saha et al., 2024).

The results of chemical analyses in the study by Ribeiro et al., 2014 showed that the alkaloids and acetogenins contained in extracts from the branches, leaves, and seeds of *Annona montana* (Annonaceae), *Aristolochia paulistana* (Aristolochiaceae), and *Casearia sylvestris* (Salicaceae) have bioactivity against *S. zeamais*. In fact, extracts from these three plants caused significant mortality ranging from 37% to 41.5%. The insect mortality observed in this study could be explained by the fact that the extracts evaluated contain secondary metabolites, including alkaloids, polyphenols, flavonoids, catechin tannins, anthocyanins, polyterpenes, sterols, and anthocyanins. These compounds are likely to have biological activities (Bley-Atse et al., 2025). The mortality elucidated by the LD_{50} and LT_{50} of the extracts in the study was very significant.

By comparison, extracts from Badi, Bete, and Iroko caused high mortality rates ranging from 50 to 100%. The results of this study are consistent with those of certain authors. Indeed, a variety of chemical molecules derived from plants are toxic, repellent, or have anti-nutritional activities for pests. Examples include molecules such as cyanogenic glycosides, glucosinolates, alkaloids, and terpenoids. Others are macromolecules and include latex or proteinase inhibitors. Their modes of action include membrane disruption, inhibition of nutrient and ion transport, inhibition of signal transduction processes, inhibition of metabolism, or disruption of hormonal control of physiological processes (Mithöfer & Boland, 2012). The results of this study corroborate those of (Gariba et al., 2021).

These authors showed that chemical molecules such as alkaloids, saponins, tannins and phenolic compounds, steroids, flavonoids, anthraquinones, and terpenoids, etc. contained in aqueous extracts ($C = 0.05$ and $C = 0.1$ g/mL) of *Lantana camara*, *Moringa oleifera*, *Citrus sinensis*, and *Hyptis suaveolens* are toxic to *S. zeamais* and *P. truncatus*. These compounds caused a decrease in egg laying and insect population, low emergence of future generations, an inhibitory effect, repellent action and an anti-feeding effect against both insect pests in the treated grains (Gariba et al., 2021). Few studies have been conducted on the use of wood extracts to control storage pests. However, some studies can be cited on the effectiveness of wood

ash (5 to 40 g/kg), particularly that of *Acacia polyacantha* and *Hymenocardia acida* against *S. zeamais*, which caused 87.11% mortality. A significant reduction in the emergence of insect offspring, a low rate of damaged grains and low weight loss were observed in the treated grains. Furthermore, the viability of the grains was not negatively affected (Jean et al., 2015).

During the bioassays carried out in the laboratory, light probably did not affect the efficacy of the wood extracts. The efficacy of the extracts was dose dependent. This study showed that exposure to light did not reduce the bioactivity of wood extracts. Nevertheless, the low mortality rate observed in certain concentrations of wood extracts in this study, particularly Iroko extract, could be due to the effect of light. Indeed, (Tsao et al., 2002) showed that aqueous extracts from the leaves and stems of the *Ailanthus altissima* tree (C= 778 ppm and 195 ppm) caused mortality of between 50 and 100% after 24 hours in larvae of mosquitoes that transmit yellow fever (*Aedes aegypti*). However, these authors also showed that the bioactivity of *A. altissima* extract was greater in light than in darkness. Indeed, certain natural compounds, particularly polyacetylene and thiophenic compounds, have high bioactivity in light (Tsao et al., 2002). These compounds may be inactive or have low bioactivity, but when exposed to light, they exhibit strong bioactivity (Campbell et al., 1982; Tsao & Eto, 1996, Tsao et al., 2002).

This information does not corroborate the findings of (Weaver et al., 1997), who claimed that lighting, particularly photoperiodic conditions (12 hours of light and 12 hours of darkness), negatively impacts the toxicity of the floral extract of the Mexican plant *Tagetes minuta* (L.). These authors correlated this fact with the presence of photoactive thiophenes, which are toxic substances against certain lepidopteran larvae. Indeed, the floral extract proved to be toxic to adult male and female corn weevils when protected from light. The toxicity was demonstrated with respective LD₅₀ and LD99 values ranging from 35 to 47 µg and 319 to 816 µg of extract per insect (Weaver et al., 1997).

S. zeamais was the most represented pest (Ra= 51.06%) in the maize stock studied. The sapwood and heartwood extracts tested showed a toxic and repellent effect against *S. zeamais*. Significant insect mortality was observed with all the doses tested. Mortality caused by sapwood extracts ranged from 66.67 to 96.67% on day 7,

while mortality caused by heartwood extracts ranged from 36.67 to 95% after only two days. Furthermore, the toxicity of the heartwood extracts from Badi, Bete and Iroko was greater (LD₅₀ of 0.0706, 0.055 and 0.1435 µL/cm² respectively on day 2) than the toxicity of the sapwood extracts (LD₅₀ of 0.0289, 0.0093 and 0.0283 µL/cm² respectively on day 7). Mortality of *S. zeamais* increased with the concentration, type of extract and duration of exposure of insects. These results could contribute to the search for alternative methods to synthetic chemical insecticides for effective and sustainable control of insect pests of stored foodstuffs.

5. Conclusion

The results of this study demonstrate that the hydroalcoholic extracts of *Nauclea diderrichii*, *Mansonina altissima*, and *Milicia excelsa* exhibit significant insecticidal activity against *Sitophilus zeamais*, the main pest of stored maize. The sapwood extracts induced higher mortality rates than those from heartwood, confirming variability in insecticidal efficacy depending on the wood part used. The low LD₅₀ and LT₅₀ values, together with the high repellency rates, highlight the strong toxic and repellent potential of these extracts against the maize weevil. The presence of bioactive secondary metabolites in these extracts likely accounts for their insecticidal and repellent effects. These findings suggest that wood extracts from these tree species could serve as promising eco-friendly alternatives to synthetic insecticides for the protection of stored products. However, further studies focusing on the isolation of active compounds, their stability, and environmental safety are needed to support the practical and sustainable use of these natural biopesticides.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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Competing Interests

Authors have declared that no competing interests exist.

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