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Investigation of synergistic effects of extracts from *Erythrophleum suaveolens*, *Azadirachta indica*, and *Chromolaena odorata* on the durability of *Antiaris toxicaria*

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A B S T R A C T

The service life of non-durable wood can be extended with inorganic preservatives, but several are harmful to the environment and non-target organisms. Recently, eco-friendly types from organic sources including plants have been used. The influence of bark extracts from *Erythrophleum suaveolens* and *Azadirachta indica*, and leaf extract from *Chromolaena odorata*, *singly and in* combinations (all at 1.5%) was investigated in field performance tests with non-durable *Antiaris toxicaria* wood. Treated and control stakes (500 × 50 × 25 mm) were exposed for 5 years. Data included extract retention, visual durability ratings, and mass and hardness losses. Retention was greatest for mixed *E. suaveolens* and *C. odorata* extract and least for single *E. suaveolens* extract. For durability parameters, non-treated stakes performed worse than treated ones. *E. suaveolens* bark-treated stakes were most durable; those treated with mixtures containing *E. suaveolens* also performed well, while stakes treated with other mixtures performed similarly to the controls, except for hardness. The mixed extracts exhibited various effects. For retention, synergism exists between *E. suaveolens* and *C. odorata*, there was antagonism between *A. indica* and *C. odorata*, while *E. suaveolens* extract reduced the retention of *A. indica*. Regarding durability, no synergism existed between effects of the mixed components. However, *E. suaveolens* bark extract enhanced *A. indica*, and *C. odorata* ingredients, while the effect of *E. suaveolens* extract was suppressed when it was mixed with the others. These extracts are potential alternatives for inorganic preservatives, especially *E. suaveolens* and its mixed extracts, as its effects enhanced the others.

1. Introduction

Wood possesses unique structural and chemical characteristics that render it desirable for a broad variety of end uses, including shelter, clothing, paper, fuel, and medicine. However, it can be degraded by many organisms, such as fungi, insects, and bacteria (Goktas et al., 2007). This has resulted in the classification of several timber species as very durable (e.g., *Milicia excela* (Welw.) C. C. Berg [odum]), durable (e.g., *Terminalia ivorensis* A. Chev. [emeri]), moderately durable (e.g., *Piptadeniastrum africana* (Hook. f.) Brenan [dahoma]), and non-durable (e.g., *Antiaris toxicaria* Lesch. [chenchen]) (Anon., 1994). Wood species that can be used in service longer without prior preservative treatment are naturally very durable, principally due to the presence of toxic chemicals (i.e., extractives) and several other inherent factors (Antwi-Boasiako, 2004). To extend the lifespan of the less durable timbers, their woods are conventionally treated with inorganic chemicals known as preservatives (Kollman and Côté, 1984). However, several that have been introduced into the market have not gained acceptance because of their harmful impurities and high environmental toxicities, high costs (Murphy, 1990), and associated work-related impacts. Consequently, chemicals such as chromated copper arsenate (CCA) have been banned in many countries including the U.S. and Japan due to their detrimental effect on the natural balance and human health (Goktas et al., 2007). At the same time, many plant extracts have been found to contain potent chemicals, including tannins, flavonoids, stilbenes, and resins, that could be employed to protect wood and wood-based products against biodeterioration. According to Goktas et al. (1998), these are mostly eco-friendly and less mammalian-toxic. Thus, recently there has been an increasing demand for wood preservatives that contain chemicals that pose no ecological and human safety problems. The use of natural plant extracts seems to be one possible approach for replacing the hazardous conventional inorganic chemical preservatives (Goktas et al., 2007).

Extracts from various parts of three plants (bark of *Erythrophleum suaveolens* (Guill and Perr) Breman and *Azadirachta indica*

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(A. Juss), and leaves of *Chromolaena odorata* (L.) R. M. King) were tested to assess their synergistic effects on the field performance of *A. toxicaria* because of their various proven toxicological characteristics. Studies have shown that extracts from these plants have biocidal properties against different biodegraders. Several species of *Erythrophleum* (including *E. guineensis E. ivorense*, *E. lasicanthum*, *E. chlorostachys*, and *E. africanum*) are extremely toxic to animals, including large mammals (Watt and Bayer-Brnadwyle, 1962), and have anti-termitic, anti-bacterial, and anti-fungal properties (Irvine, 1961; Abbiw, 1990). *E. suaveolens* is abundant locally and has been shown to be efficacious against termites (Serwaa, 2007). *A. indica* has also been proven to have several medicinal properties. Neem powder is used to control plant fungi, nematodes, and termites (Irvine, 1961; Williams, 1981), while *C. odorata* possesses anti-fungal and anti-bacterial properties (Liogier, 1997). Investigation of the synergistic interactions of mixed extracts from eco-friendly plant sources on the durability of timbers under long-term field conditions is a significant novelty. Antwi-Boasiako (2004) achieved effective collection of significant amounts of extractives from plant sources using water, rather than expensive inorganic and organic solvents. Recently, water-borne preservatives have been increasingly used to treat wood products due to their being more environmentally benign than oil-borne and other types. The former lack odour, keep treated surfaces dry, and are the best choice when a high degree of human contact is involved (De Groot et al., 1996). The rationale of the present investigation was to determine the most effective extract combinations, which can be used as wood preservatives. It is anticipated that once proved efficacious, these relatively cheap and more environmentally-friendly water-borne organic preservatives could be employed as replacements for the conventional types.

2. Materials and methods

2.1. Preparation of extracts and wood samples for impregnation

A. indica and *E. suaveolens* barks and *C. odorata* leaves obtained from Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana, in the semi-decidious forest zone, were air-dried to 12–14% moisture content (mc) and milled to a fine particle size (40–60 mesh) with a Wiley mill. Equal weights (1450 g) of each powdered sample were added to distilled water (1:10), stirred thoroughly for 45 min, and left to stand for 48 h. The liquid was decanted and sieved through mesh (1 mm) and clarified by centrifugation at 1500 × g for 45 min. The supernatant liquid was then decanted from the precipitate. Concentration of each liquid (i.e., dry powdered sample [grams] in a known amount of distilled water [milliliters]) was determined and standardized at 1.5%. Stakes (500 × 50 × 25 mm) were prepared from a disc (120 cm in diameter) taken from a matured *A. toxicaria* butt (2 m from the forest ground) from Mim, Ghana. The stakes were air-dried (to 12–14% mc) and impregnated with the various plant extracts.

2.2. Impregnation of *A. toxicaria* stakes using the pressure method

Ten stakes of *A. toxicaria* were impregnated (at 124 °C and 1.2 bar pressure for 3 h) with 1.5% of each extract (4000 ml) with all stakes totally submerged. Each group of 10 stakes were similarly treated with four extract combinations of *E. suaveolens* and *A. indica*, *E. suaveolens* and *C. odorata*, *A. indica* and *C. odorata*, and *E. suaveolens*, *A. indica*, and *C. odorata*. Impregnation was repeated for other sets of replicate stakes and the volume of extract absorbed by each block was determined. Ten *A. toxicaria* stakes were not treated and served as controls.

2.3. Mass and hardness determination of stakes

All the air-dried stakes (treated and untreated) were weighed and subjected to hardness testing using the Pilodyn 6J [Proceq SA] wood density meter. The depth of its pin penetration in each stake was taken as its initial hardness, with 0 mm = very hard and 40 mm = very soft (Brunner and Grüsser, 2006). Each stake was re-weighed and hardness was re-measured at 12–14% mc after field exposure. Corrected oven-dry masses of the samples were determined from the constant weights of three stakes at 103 ± 5 °C. The moisture content of each sample was then calculated using the formula:

$$\text{Mc}\ (\%) = \frac{\text{Fresh weight} - \text{Oven-dry weight}}{\text{Oven-dry weight}} \times 100$$

The average moisture content of the three stakes for each treatment was then used to determine the corrected oven-dry masses of their counterpart replicates as:

$$\text{Corrected oven-dry mass (g)} = \frac{100 \times \text{Fresh weight of sample}}{100 + \text{mc}}$$

The corrected oven-dry mass for each stake was taken as its initial mass before field exposure.

2.4. Durability test for treated and untreated *A. toxicaria* stakes

Each stake was inserted to about one third of its length at an interval of 50 cm using completely randomized design (CRD) at a test site (6.5 m × 5.5 m) at the Faculty of Renewable Natural Resources (FRNR) Research Farm at KNUST (Plate 1). Regular field inspection of the stakes was done weekly for colour change, presence of fruiting bodies, fungal decay, termite runways, and the level of termite activity through grazing. After field exposure, visual durability rankings were made according to EN 252 (Anon., 1989), where 0 = no sign of attack, 1 = slight attack, 2 = moderate attack, 3 = severe attack, and 4 = failure.

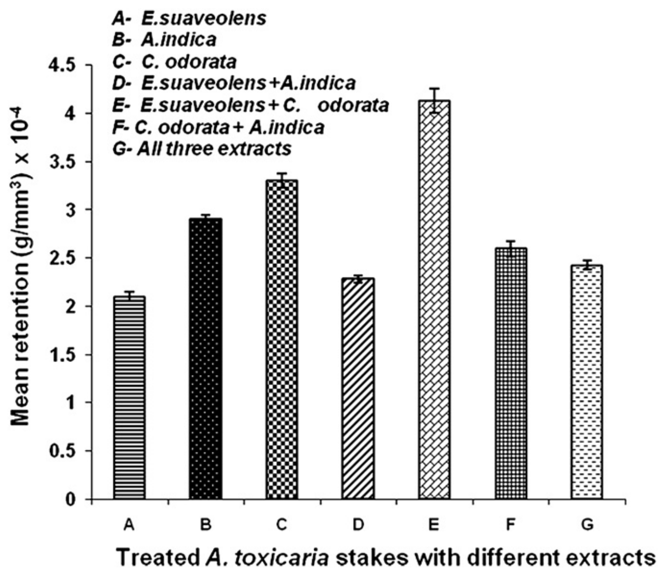

Fig. 1. Mean retentions for the different extracts impregnated into *A. toxicaria* stakes. NB: Bars = standard errors.

Table 1
ANOVA for mean extract retention levels for *A. toxicaria* treated stakes.

Source of variation	Sum of squares	Degrees of freedom	Mean sum of squares	*F*-ratio
Treatments	30.6234	6	5.1039	40.83*
Errors	2.7341	63	0.0506	
Total	151.4875	69		

*Significant ($p < 0.05$).

Table 3
ANOVA for mean visual durability ratings for *A. toxicaria* stakes.

Source of variation	Sum of squares	Degrees of freedom	Mean sum of squares	*F*-ratio
Treatments	120.5875	7	17.2267	38.0*
Errors	28.5375	72	0.4529	
Total	151.4875	79		

*Significant ($p < 0.05$).

3. Results

3.1. Retention of plant extracts by A. toxicaria stakes

A variation in retention levels was seen for the different extracts in the *A. toxicaria* stakes after impregnation (Fig. 1). For the single extract treatments (A–C), stakes treated with *C. odorata* leaf extract (C) had the highest retention, followed by those treated with *A. indica* bark extract (B), and then lastly *E. suaveolens* (A) treated stakes. For the mixed extracts (D–G), *E. suaveolens* and *C. odorata* treated samples (E) had the maximum retention, which was far greater than the retention levels of those treated with their individual extracts; the lowest was recorded for those treated with *E. suaveolens* and *A. indica* (D). Generally, replicates treated with either single *C. odorata* (C) extract or its combinations (i.e., E–G), as especially with *E. suaveolens* (unlike its single extract), recorded greater retention values. Mixed *A. indica* bark and *C. odorata* leaf extract (F) reacted well, and were retained in the stakes more than their single extracts (i.e., B and C, respectively). Differences between the various retention rates from ANOVA (Table 1) and Duncan's Multiple Range Test (Table 2) were significant ($p < 0.05$). The general ranking for extract retention was: E > C > B > F > G > D > A.

3.2. Resistance of treated and untreated A. toxicaria stakes to biodegradation in the field

The level of resistance of all *A. toxicaria* stakes to attack by termites and other degraders after field exposure was analyzed using their visual durability ratings, mass losses, and hardness losses, with data trends given below:

3.2.1. Visual durability ratings for A. toxicaria stakes after field exposure

Mean visual durability ratings for *A. toxicaria* treated and untreated stakes show significant differences ($p < 0.05$) between treatments (Table 3). According to the Duncan's Multiple Range Test (Table 4) for the single extract treatments, *A. indica* (B) and *C. odorata* (C) treated stakes recorded the highest mean visual durability ratings (i.e., they performed the worst) similar to the untreated stakes (T), while those impregnated with *E. suaveolens* extract (A) were most resistant to biodegradation (Fig. 2). Generally, stakes impregnated with *E. suaveolens* extract mixtures performed well, especially those treated with mixed *E. suaveolens* and *A. indica* (D), while no significant differences existed between retentions for *E. suaveolens* and *C. odorata* (E) and *E. suaveolens*, *C. odorata*, and *A. indica* (G) treated stakes (Fig. 2, Table 4). The visual durability ranking for extract retention was: T = B = C = F > E = G > D > A.

3.2.2. Mean percentage mass losses for A. toxicaria stakes after field exposure

Table 5 shows that generally the differences between the treatment means for mass loss were significant ($p < 0.05$). For the single extract applications, those treated with *C. odorata* (C) and *A. indica* (B) only were less durable and had greater mean percentage mass losses than the control stakes (T). Stakes treated with *E. suaveolens* (A) recorded the least mass loss and were generally the most durable (Fig. 3). Mixed-extract treated stakes with *C. odorata* and *A. indica* (F) lost most biomass and were, in equal measure, least durable. However, all those impregnated with extracts containing *E. suaveolens* (D, E, and G) performed very well in the field, with no significant differences ($p < 0.05$) between them (Table 6). The general ranking was as follows: C = T > B = F > D = E = G > A.

3.2.3. Mean hardness losses for A. toxicaria stakes after field exposure

Both treated and untreated *A. toxicaria* stakes recorded losses in hardness at the end of the test with significant differences ($p < 0.05$) between them (Table 7). However, the controls (T) lost more biomass (or hardness) and became softer than the treated stakes except for those treated with *C. odorata*, which lost hardness similarly to the controls. Besides the *C. odorata* treated stakes, treatment with individual extracts shows those impregnated with *A. indica* extracts (B) also lost hardness more than those treated with *E. suaveolens* (A) (Fig. 4). Generally, stakes treated with mixed extracts (D, E, F, and G) recorded the least losses in hardness with no significant differences ($p < 0.05$) between them (Fig. 4, Table 8). Thus, the hardness loss ranking for

Table 2
Duncan's Multiple Range Test for mean extract retentions for *A. toxicaria* treated stakes.

Treatments	No. of replicates	Mean (g/mm^3) × 10^{-4}	SE	*Duncan's Grouping
E. suaveolens	10	2.0564	0.0047	G
A. indica	10	2.8700	0.0560	C
C. odorata	10	3.3394	0.0727	B
E. suaveolens & *A. indica*	10	2.2848	0.0380	F
E. suaveolens & *C. odorata*	10	4.1292	0.1233	A
C. odorata & *A. indica*	10	2.5959	0.0759	D
E. suaveolens, *A. indica* & *C. odorata*	10	2.2848	0.0474	E

*Means with the same letters are not significantly different ($p < 0.05$).

Table 4
Duncan's Multiple Range Test for mean visual durability ratings for *A. toxicaria* stakes.

Treatments	No. of replicates	Mean[a]	SE	*Duncan's Grouping
E. suaveolens	10	0.100	0.090	D
A. indica	10	3.000	0.406	A
C. odorata	10	3.200	0.422	A
E. suaveolens & *A. indica*	10	0.600	0.300	C
E. suaveolens & *C. odorata*	10	0.900	0.300	BC
C. odorata & *A. indica*	10	2.700	0.433	A
E. suaveolens, *A. indica* & *C. odorata*	10	1.100	0.010	B
Control	10	3.300	0.643	A

*Means with the same letters are not significantly different ($p < 0.05$).
[a] EN 252 ranking: 0 = No sign of attack; 1 = Slight attack; 2 = Moderate attack; 3 = Severe attack and 4 = Failure (Anon., 1989).

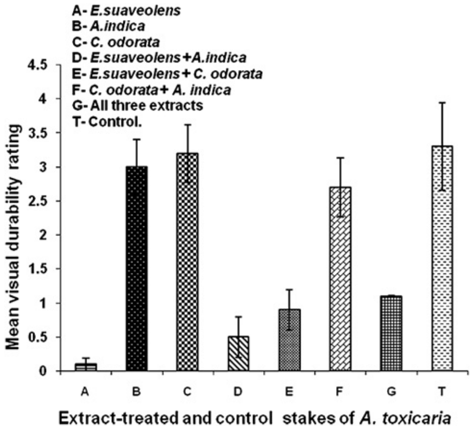

Fig. 2. Mean visual durability ratings for *A. toxicaria* stakes after field exposure. NB: Bars = standard errors.

the stakes is: T = C > B = G = D = E = F > A. Generally, as for mass losses and visual durability ratings (Figs. 2 and 3, respectively), hardness loss results have also shown that extract performance is best in *E. suaveolens* treated stakes (A) as well as stakes impregnated with mixed extracts of *E. suaveolens*, while the others performed poorly and are in the same group as the controls (except for hardness).

4. Discussion

4.1. Extract retention by stakes of A. toxicaria

Ofori and Bamfo (1994) found *A. toxicaria* sapwood and heartwood to be, in general, moderately resistant to preservative treatment (at 1104 kPa for 1 h or more, or at 966 kPa for 2 h or more). However, it is worth noting that even though the treatability of *A. toxicaria* is classified moderate, large-scale variation in retention exists among the various water-based extracts used in this study. Haygreen and Bowyer (1996) reported that different plants contain a variety of extracts with varied chemical properties that enable them to perform different functions such as retention. For instance, although the extracts are all from plant sources, stakes treated with *C. odorata* and *E. suaveolens* had the highest and lowest levels of retention, respectively, for the single extract treatments. The differing retention levels can be attributed to the fact that the extracts came from different plant parts (i.e., barks and leaves). Besides the viscosity and chemical nature of extracts, these two processes (impregnation and retention) also depend on wood properties including its anatomy, cellular components, chemical make-up, and, according to De Groot et al. (1996), penetrability variation among the different cell or tissue types. Individually, *E. suaveolens* extract was less retained than that of *C. odorata*; however, their mixture achieved the highest retention level among all the different treatments. This could be attributed to increased reactivity of the mixed chemical compounds from the extracts and the various binding sites on the wood where they adsorbed, which greatly aided retention (Wegner et al., 1989). Since the extract mixtures were all of the same proportion and the treatment conditions as well as the treated wood species (*A. toxicaria*) were also the same, chemicals in the *E. suaveolens* and *C. odorata* extract mixture (E) exhibit significantly strong synergism in terms of retention as against antagonism for *A. indica* and *C. odorata* mixed extract. There was no synergistic interaction between *A. indica* and *E. suaveolens* mixed extracts; the latter reduced the effect of *A. indica* (Fig. 1).

Table 5
ANOVA for mean mass losses for *A. toxicaria* stakes after field exposure.

Source of variation	Sum of squares	Degrees of freedom	Mean sum of squares	*F*-ratio
Treatments	10 546.8380	7	1506.6	8.47*
Errors	11 202.1795	72	177.8124	
Total	23 769.5520	79		

*Significant ($p < 0.05$).

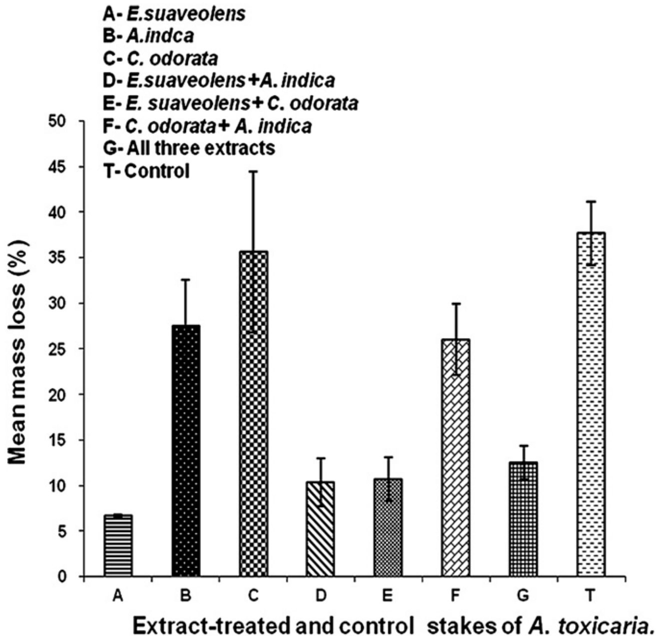

Fig. 3. Mean percentage mass losses for *A. toxicaria* stakes after field exposure. NB: Bars = standard errors.

4.2. Visual durability ratings for treated and untreated stakes of A. toxicaria

After the samples were cleared of all debris at the end of the investigation, it was observed that stakes treated with any of the extracts (single or mixed) had scanty or no visible signs of fungal stains, moulds, or fructifications. This is a clear indication that extracts from all the plants contain anti-fungal properties, which have been reported for *A. indica* by Abbiw (1990), for *Erythrophleum* spp. (e.g., *E. guineense*) by Adeoye and Oyedapo (2004), and for *C. odorata* by Liogier (1997). However, the visual durability ratings for the *A. toxicaria* treated stakes show that against termites, those impregnated with extracts of *E. suaveolens* bark have the lowest

Table 6
Duncan's Multiple Range Test for different mean mass losses for *A. toxicaria*.

Treatments	No. of replicates	Mean (%)	SE	*Duncan's Grouping
E. suaveolens	10	6.640	0.2045	D
A. indica	10	27.450	5.1329	AB
C. odorata	10	35.600	8.7835	A
E. suaveolens & *A. indica*	10	10.360	2.4004	C
E. suaveolens & *C. odorata*	10	10.650	2.4004	C
C. odorata & *A. indica*	10	26.040	3.8597	AB
E. suaveolens, *A. indica* & *C. odorata*	10	12.520	1.8566	C
Control	10	37.620	3.5057	A

*Means with the same letters are not significantly different ($p < 0.05$).

Table 7
ANOVA for mean hardness losses for *A. toxicaria* stakes.

Source of variation	Sum of squares	Degrees of freedom	Mean sum of squares	*F*-ratio
Treatments	312.1375	7	44.5914	1.86*
Errors	1508.175	72	23.3883	
Total	215.3875	79		

*Significant ($p < 0.05$).

Table 8
Duncan's Multiple Range Test for mean hardness losses for *A. toxicaria* stakes.

Treatments	No. of replicates	Mean (mm)	SE	*Duncan's Grouping
E. suaveolens	10	3.900	0.3215	D
A. indica	10	1.050	0.5850	B
C. odorata	10	5.700	2.3021	A
E. suaveolens & *A. indica*	10	5.400	0.7643	BC
E. suaveolens & *C. odorata*	10	1.900	0.8432	BC
C. odorata & *A. indica*	10	1.850	0.6862	BC
E. suaveolens, *A. indica* & *C. odorata*	10	2.700	0.7526	B
Control	10	6.800	0.8654	A

*Means with the same letters are not significantly different ($p < 0.05$).

ratings (i.e., 0, a class indicating no sign of attack in the field [Anon., 1989]). Those treated with individual *C. odorata* extract and all its mixtures are of class 3 (i.e., severe attack). Extract mixture involving *E. suaveolens* bark extract performed effectively well (compared to its single extract) in imparting durability to *A. toxicaria* (i.e., 1, which denotes slight attack). Once again, *E. suaveolens* extract contributed effectively in such a mixture to reduce the deterioration of the stakes as compared to the contribution made by the mixed *A. indica* and *C. odorata* extracts. In treating wood with different biocides, some biodegraders (e.g., insects and fungi) are not repelled or destroyed by particular chemical treatments. Thus, in order to protect wood against a broader range of organisms, preservative combinations are sometimes used. However, it has been stressed (Anon., 1996) that some combinations have been found to have a greater effect than the sum of their components and are considered synergistic. There was no synergistic effect between the extract components of *A. indica* (B) and *C. odorata* (C), nor between each of these and *E. suaveolens* extract. However, the active ingredients of *E. suaveolens* enhanced the performance of *A. indica* (B) and *C. odorata* (C) extracts in the field.

4.3. Mean percentage mass losses for treated and untreated stakes of A. toxicaria

That the untreated *A. toxicaria* stakes performed worst for all the parameters used to test timber biodeterioration in the field confirms the durability classification made in 1994 (Anon.) that grades it as having low natural durability. Hence, its untreated stakes were unsurprisingly severely attacked, which is shown in their higher mean percentage mass losses. *C. odorata* single-extract-treated stakes also performed badly. Works by Liogier (1997) showed that *C. odorata* has anti-fungal and anti-bacterial properties but very low termite resistance. The numerous termite runways and signs of degradation, such as cavities and grazed parts, on the *C. odorata* treated stakes suggest that the attack was predominantly caused by termites, which are the greatest biodegraders in the test-field (Antwi-Boasiako, 2004). Thus, in support of Liogier's (1997) assertion, the loss in mass in the *C. odorata* treated stakes could be largely attributed to the low termite resistance ability of extract from the *C. odorata* shrub. *E suaveolens* has been reported to be very durable, especially against termites (Hawthorne and Gyakari, 2006). Irvine (1961) and an anonymous author Anon. (1999) attributed its termite- and fungi-proof properties and overall natural resistance to the toxic nature of its extracts, which is likely due to several alkaloids (e.g., erythrophleine) as well as minute quantities of other alkaloid derivatives (including cassaine, nor-cassaidine, and homophleine). Thus, stakes treated with *E. suaveolens* bark extract were hardly degraded by the main biodeteriorators (i.e., termites) at the test site. The ability of *E. suaveolens* bark extract to resist biodegraders such as termites is also evident in stakes treated with all the extract mixtures containing *E. suaveolens* (i.e., D, E, and G), which generally performed well in the field. The lower mean percentage mass losses of the stakes are not significantly different ($p < 0.05$) but are slightly less than those treated with *E. suaveolens* single extract. However, the mixture of *E. suaveolens* extract with either *A. indica* or *C. odorata* extracts showed essentially no synergism, as the mass loss values of stakes treated with mixed extracts involving *E. suaveolens* were lower than that of its single extract. Nevertheless, the effects of *A. indica* and *C. odorata* extracts are once again enhanced by the

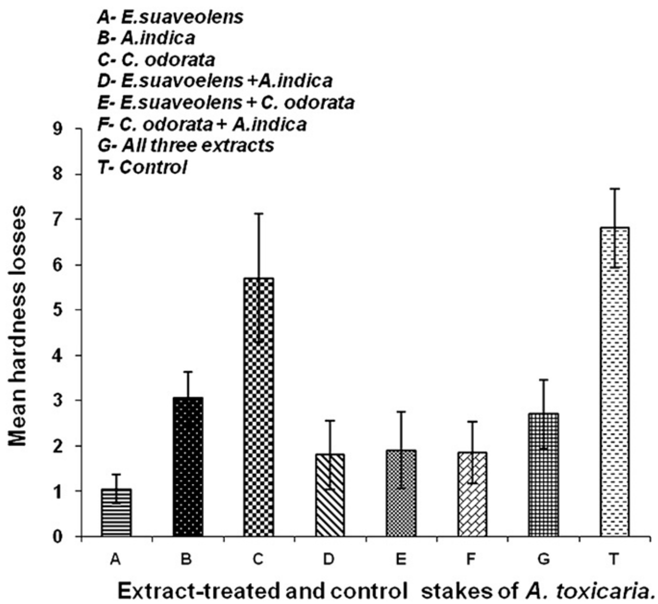

Fig. 4. Mean percentage hardness losses in *A. toxicaria* stakes after field exposure. NB: Bars = standard errors.

Plate 1. Freshly inserted *A. toxicaria* (treated and untreated) stakes at FRNR test-field.

ingredients of *E. suaveolens* extract, which had a positive effect on all mixed-extract treated stakes with *E. suaveolens* to resist biodegradation more than single-extract-treated stakes with *A. indica* or *C. odorata*. The interaction between extracts of *A. indica* and *C. odorata* is not synergistic. *A. indica* is also reported to be anti-termiticidal, besides its anti-fungal properties (Mbuya et al., 1994), which are due to its environmentally friendly and target-specific active ingredient, that is, azadirachtin (www.homestead.com/purofelasis/files/neem.html.2003) (Ramasamy, 2008). Nevertheless, it was shown that *A. indica* extract resistance against the outdoor biodegraders (especially termites) is not as effective as that of *E. suaveolens* extract; nor did it perform better in a mixture with *C. odorata*.

4.4. Mean hardness losses for stakes of *A. toxicaria* after field insertion

Tearing away wood tissue to the depth of penetration of the pin of the pilodyn is often used as a measure of wood hardness, especially before and after field exposure. Accordingly, Brunner and Grüsser (2006) suggested that stakes that record great penetration depths lose immense hardness. Wood hardness loss on exposure to biodegraders can usually be employed as an indicator of deterioration, as these organisms feed on wood cells and wall components, thereby weakening the tissues. Deterioration can adversely affect wood's hygroscopic characteristics, which contribute to its softening, thus facilitating greater pilodyn penetration. As previously outlined, the controls were accordingly the softest. However, for the treated samples, those impregnated with single *E. suaveolens* and *C. odorata* extracts had the lowest and highest hardness losses, respectively. Moreover, the low hardness losses recorded for all stakes treated with extract mixtures containing *E. suaveolens* extract show they were not seriously degraded in the field; this was similarly manifested by their small visual durability ratings and mass losses.

The extract performance in the treated stakes has revealed that the single extract of *E. suaveolens* has been the most efficient for all the durability parameters investigated. Those impregnated with mixed extracts comprising *E. suaveolens* could also resist degradation very effectively. However, except for hardness loss, the other mixed extracts usually performed as poorly as the controls in visual durability ratings. The results show that, in general, there was no synergistic effect for the hardness properties of stakes treated with mixed extracts, even those containing *E. suaveolens*, which did not increase the hardness properties of the stakes except in its single extract form. However, single extract treatment performance of stakes in the field show that *E. suaveolens* extract is established as the most effective in conferring durability, and that extract of *C. odorata* is the least effective for almost all the durability parameters employed. Furthermore, although wood treatment involves impregnation, often with fluid-borne preservatives, protection of non-durable timbers depends on uniform penetration of the preservative (often offered by the pressure process) and its retention. The outstanding retention rates for *E. suaveolens* and *C. odorata* extract mixture means they can equally offer much protection for non-durable wood materials. In many applications, the use of water-borne preservatives is preferred, because of the odours, flammability, and often toxic nature of other liquid hydrocarbon solvents (Anon., 1996). As for other inorganic preservatives, Permadi (1995) reported in De Groot et al. (1996) that the commonly used water-borne preservative CCA is banned in many nations, including Indonesia. Goktas et al. (2007) reported the same for the U.S. and Japan. The use of these extracts and their mixtures, particularly those including *E. suaveolens*, as organic preservatives in the wood industry looks like a very appealing prospect since they also employ the most inexpensive solvent (i.e., water) for their extraction. There is the potential for the utilization of natural preservatives (such as extracts from the three plants, especially *E. suaveolens* bark) particularly those whose active ingredients are recognized to be more eco-friendly.

5. Conclusions

Retention differences for the water-borne extracts in the stakes of *A. toxicaria*, a relatively diffuse porous and moderately treatable hardwood, most likely reflect viscosity variations among the extracts, besides the chemical constituents of their active ingredients, which need further examination.

As synergism in retention strongly exists for the mixed extracts of *E. suaveolens* and *C. odorata*, for effective retention, their mixed extracts are recommended.

Contrary to expectations, mixed extracts used as wood organic preservatives do not always enhance field performance of non-durable woods, as their interaction is not always synergistic. However, instead of employing the single extract of either *A. indica* or *C. odorata*, using their mixtures containing *E. suaveolens* and other equally effective organic types is advocated.

The possible adverse effects or risks of these extracts need evaluation. If proven safe, well packaged *A. indica* and *C. odorata* single extracts could be employed to control fungal stains and moulds on easily attacked freshly harvested logs.

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