SHORT COMMUNICATION

VOLATILISATION LOSSES FROM SURFACE-APPLIED NITROGENOUS FERTILISERS IN THE SUGARCANE-GROWING SOILS OF ZIMBABWE: LABORATORY-SCALE STUDY

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Abstract

The volatilisation of nitrogen (N) fertiliser represents a major pathway of nutrient loss in sugarcane cultivation, which potentially leads to reduced crop yields and inefficient fertiliser use. This study quantified the ammonia volatilisation losses from surface-applied nitrogenous fertilizer, under controlled laboratory conditions, using soils from Zimbabwe's sugarcane-growing regions. Four N sources, white urea, carbon-coated urea, urease-inhibited urea and ammonium nitrate were evaluated across soils with a varying pH and texture, under laboratory conditions. The results showed that volatilisation losses were highest in alkaline soils (pH>7.0), with white urea losing up to 85% of its N content over a 14-day period. Among the fertilisers, white urea exhibited the highest volatilisation, followed by carbon-coated urea and ammonium nitrate, while urease-inhibited urea showed the lowest losses. Soils with a higher clay content (greater than 35%) exhibited significantly lower volatilisation than sandy soils. These findings highlight the critical influence of soil properties on nitrogen use efficiency, and they emphasise the need for informed fertiliser selection, in order to enhance productivity and environmental sustainability in sugarcane farming.

Keywords: nitrogen volatilisation, urea, urease inhibitor, ammonium nitrate, sugarcane, soil properties

Introduction

Nitrogen is a vital nutrient in sugarcane production, which directly influences biomass accumulation and the sugar yield (Meyer *et al*., 2007; Boschiero *et al*., 2020). To meet the high nutrient demands of sugarcane, large quantities of nitrogenous fertilisers are routinely applied (Mthimkhulu & Miles, 2017; Titshall *et al*., 2023). In Zimbabwe, the most commonly-used nitrogen sources include urea, Ammonium Nitrate (AN), and Calcium Ammonium Nitrate (CAN), with urea being the preferred choice, due to its high nitrogen content (46%) and cost-effectiveness (Clowes

& Breakwell, 1998; Degaspari *et al*., 2020). However, urea is highly susceptible to ammonia volatilisation, especially when it is surface applied, without incorporation (Oliveira *et al*., 2023).

Nitrogen losses through volatilisation, along with leaching, runoff and denitrification, significantly reduce the fertiliser-use efficiency and they increase the environmental risks (Yang *et al*., 2018). Ammonia volatilisation occurs when urea is hydrolysed to ammonium, which is then lost as gaseous ammonia, particularly under a high pH, warm temperatures and partially wet conditions (Sigurdarson *et al*., 2018).

In order to mitigate against nitrogen losses, fertiliser innovations have been developed, such as coated urea and urease inhibitors. Despite their availability, many farmers remain unaware of their benefits, or they lack guidance on their effective use, particularly in the wake of Zimbabwe's land-reform programme, which introduced a wave of inexperienced farmers.

This study aimed to quantify the volatilisation losses from various nitrogen fertilisers under the different soil conditions found in Zimbabwe's sugarcane-growing regions, under laboratory conditions. By identifying the influence of the soil pH and texture on nitrogen losses, the research provides actionable insights into fertiliser selection and the management for improved nitrogen-use efficiency and sustainable sugarcane production.

Materials and Methods

Experimental site

The experiment was conducted under laboratory conditions at the Zimbabwe Sugar Association Experiment Station (ZSAES), which is located in Chiredzi in the south-eastern Lowveld of Zimbabwe, along the Ngundu-Tanganda road (21°01'57"S; 31°36'58"E; 430 m above sea level). The region is semi-arid, and it receives an average annual rainfall of 550-600 mm, with hot summers (a daily max >30°C), short cool winters and night-time temperatures that range from 6-9°C.

The Zimbabwe Sugar Industry (ZSI) features two dominant soil types, namely, basalt-derived self-churning clays (Vertisols) and siallitic soils derived from gneisses (Clowes & Breakwell, 1998). Vertisols are prevalent in the Hippo Valley, while siallitic soils dominate the Triangle, Mkwasine and ZSAES areas. This study was conducted in the ZSAES Industrial and Agricultural Chemistry Laboratory, using soils that were sampled from the major sugarcane-growing regions.

Sampling and sample preparation

Soil selection was guided by the 2023-2024 ZSAES Agricultural and Industrial Chemistry soil database, which contains historical data on the pH, texture and clay content. Targeted soils were sampled from Triangle, the Hippo Valley, Mkwasine and ZSAES, using a Dutch auger at a depth of 0-30 cm, which corresponds to the primary root zone for sugarcane (Clowes & Breakwell, 1998). A diagonal sampling technique was employed, as described by Chikazaza *et al*. (2022).

The samples were transported in polythene bags and they were air-dried upon arrival at the laboratory. They were crushed with a wooden mallet to break the aggregates and then sieved through a 2 mm mesh (Chikazaza *et al*., 2022).

Soil analysis

All soil samples were analysed for their physico-chemical properties, including their pH, Electrical Conductivity (EC), total nitrogen content, water-holding capacity and texture. The soil pH was determined by using a 1:5 volume-to-volume suspension of soil in a 0.01 M calcium chloride ($CaCl_2$) solution, and the measurements were taken by using a Mettler Toledo Seven Excellence multiparameter meter. The electrical conductivity was measured by using the same instrument on a 1:5 suspension of soil in distilled water. Soil texture was assessed by using the Bouyoucos hydrometer method, as outlined by Beretta *et al*. (2014), which quantifies the proportions of sand, silt and clay. The total soil nitrogen was quantified by using the Kjeldahl digestion method (FAO, 2021), which involves acid digestion, distillation and titration, to determine the concentration of ammoniacal nitrogen.

Experimental set-up and design

The experiment was laid out in a Completely Randomised Design (CRD), following a 2×4 factorial arrangement. Factor A consisted of two soil characteristics, the pH and clay content, while Factor B included four fertiliser treatments: white urea, carbon-coated urea, urease-inhibited urea, ammonium nitrate, as well as a control treatment with no fertiliser. The control was included, in order to verify that the observed nitrogen losses were due to the applied fertilisers, and not to experimental error.

For each treatment, 50 grams of air-dried soil were accurately weighed and placed into individual petri dishes. Fertiliser granules were uniformly applied on the soil surface to deliver a nitrogen rate that was equivalent to 0.46 grams of N per dish. The soil moisture was brought to the field capacity by using distilled water, and the moisture content was kept constant throughout the experimental period.

The treated soils were left to volatilise under controlled laboratory conditions, with the assumption that the nitrogen loss would primarily be influenced by the varying soil pH and texture. Each experimental set, one focusing on the pH and the other on the texture, included 15 treatments, which were each replicated three times, resulting in 45 experimental units per set. Volatilisation was monitored over a period of 14 consecutive days, during which daily observations were made. Nitrogen concentrations were measured both at the beginning of the experiment (to establish the baseline levels) and at the end of the volatilisation period, by using the Kjeldahl method. Nitrogen loss, due to volatilisation, was estimated as the difference between the total nitrogen applied and the residual nitrogen remaining in the soil after the experimental period.

Statistical analysis of data

The data were analysed by using Genstat Release 23.1. A two-way ANOVA was performed to test for significant differences in nitrogen volatilisation among the treatments. The treatment means were separated by using the Least Significant Difference (LSD) at a 5% significance level.

Results and Discussion

Characteristics of the soils used in the study

The soils used in this study varied in their pH and clay content, to represent the typical sugarcane-growing conditions in Zimbabwe. In the pH experiment, the pH values ranged from 4.88 to 8.02, while in the texture experiment, the soils had a clay content that ranged from 9% to 50%.

Effect of pH on ammonia volatilisation

Ammonia volatilisation losses were monitored over 14 days by using five nitrogen fertiliser treatments across soils with low (less than 4.88), medium (4.88 to 6.20) and high (greater than 8.02) pH levels. The results showed a strong positive correlation between the increasing soil pH and nitrogen loss (F=3193.68; p<0.001), with the highest losses being observed in alkaline soils. White urea exhibited the greatest susceptibility to volatilisation across all pH levels, particularly at a high pH, while urease-inhibited urea showed the lowest losses (Figure 1).

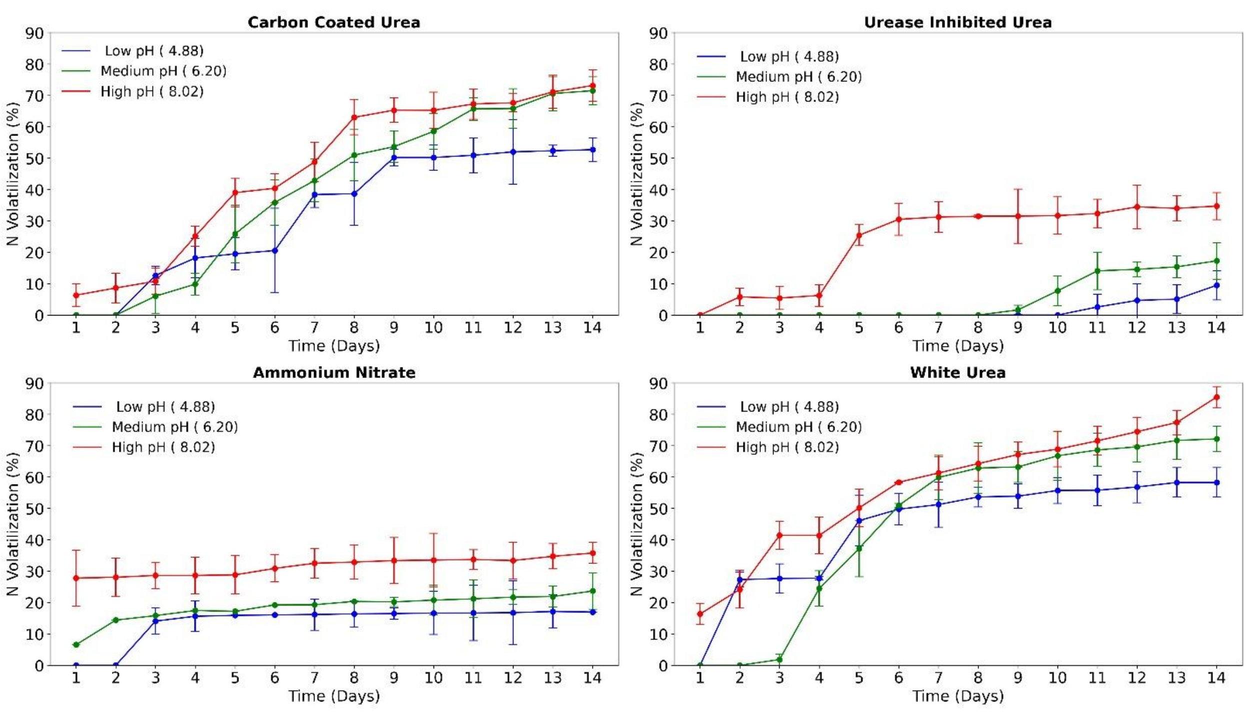

Figure 1. Effect of pH on volatilisation losses from different fertilisers over 14 days

This trend aligns with the chemical equilibrium between the ammonium ions and the ammonia in soil. A higher pH increases the hydroxide ion concentration, shifting the equilibrium toward ammonia, which is volatile and easily lost to the atmosphere (Freney *et al*., 1983; du Preez & Burger, 1988). The higher losses in white urea from this study (up to 80%), compared to the losses of about 50% from the du Preez and Burger (1988) study, may be due to the longer monitoring duration of 14 days vs 3 days, the differences in their measurement methods, and the surface application of fertilisers without soil incorporation, under laboratory conditions.

Effect of the fertiliser type on volatilisation at different pH levels

The fertiliser type significantly influenced the volatilisation losses ($F=19142.42$; $p<0.001$). The cumulative nitrogen losses were as follows (Figure 2): white urea (49.39%), carbon-coated urea (39.58%), ammonium nitrate (21.25%), urease-inhibited urea (10.18%) and the control (0.34%). The losses were highest in the high-pH soils (mean = 31.95%), followed by the medium (21.89%) and low-pH soils (18.61%).

The effectiveness of urease-inhibited urea can be attributed to the presence of Agrotain, which delays urea hydrolysis and reduces the early release of ammonia. In contrast, white urea hydrolyses rapidly, forming ammonium carbonate, which elevates the local pH and promotes volatilisation. Carbon-coated urea showed slightly-reduced losses, which are likely due to the microbial stimulation around the granule that moderates hydrolysis. The control plots showed negligible losses, which confirmed the validity of the experimental set-up.

A significant interaction was observed between the fertiliser type and the soil pH ($F=320.98$; $p<0.001$). The white urea losses increased markedly across the defined soil pH categories: 44.42% for a low pH (<4.88), 46.40% for a medium pH (4.89-6.20) and 57.33% for a high pH (>6.21). In contrast, urease-inhibited urea losses were minimal at a low (1.51%) and medium pH (5.17%), and they increased only moderately under a high pH (23.85%). The daily volatilisation followed a sigmoidal trend, namely, slow at first, accelerating mid-period and plateauing towards Day 14. The white urea lost up to 85% of its N under a high pH by Day 14, while the urease-inhibited urea showed delayed and limited losses (Figure 2).

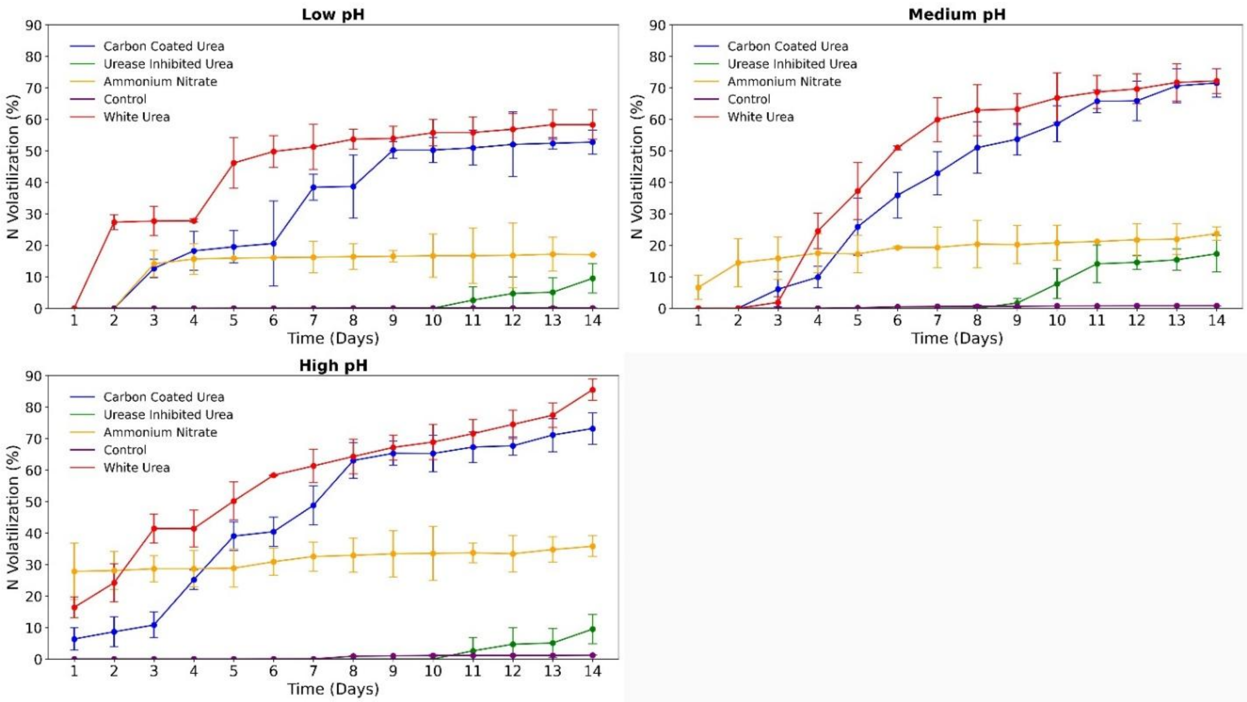

Figure 2. Volatilisation loss (%) of fertilisers at a low (a), medium (b) and high (c) pH over 14 days

Effect of soil texture (clay content) on volatilisation

The soil texture also significantly affected the volatilisation losses ($F=143.75$; $p<0.001$). The average losses of all the fertilisers were inversely related to the clay content, with high-clay soils (greater than 35% clay) averaging a 18.16% loss, compared to 23.21% in medium-clay (15- 35% clay) and 24.11% in low-clay soils (less than 15% clay). Across all textures, the ranking of fertilisers by loss remained as follows: white urea > carbon-coated urea > ammonium nitrate > urease-inhibited urea (Figure 3).

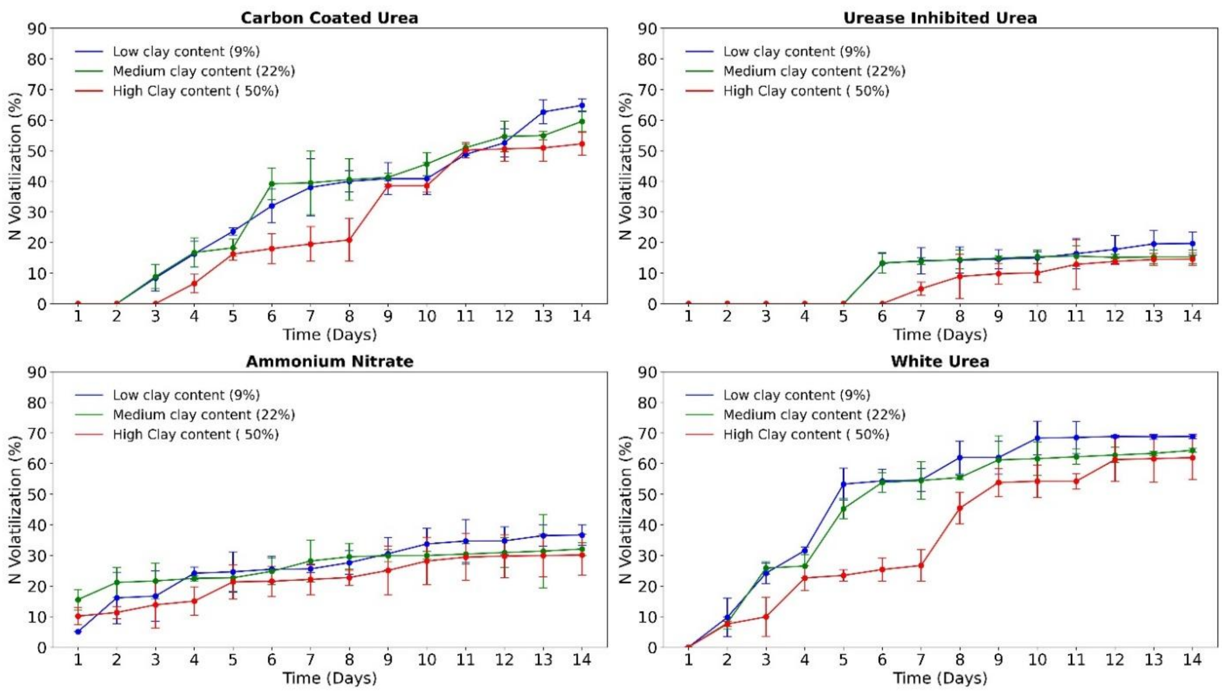

Figure 3. Effect of texture on ammonia volatilisation

High clay soils retain more moisture and have a higher Cation Exchange Capacity (CEC), which enhances their ammonium ion retention and reduces NH_3 volatilisation (Barakan & Aghazadeh, 2020). In contrast, sandy soils with a low clay content have a lower buffering capacity, a greater pore space and a lower water retention, which increases their susceptibility to volatilisation.

The findings contrast with field-based studies, like Rochette *et al*. (2013), who reported 2.8-11.6% ammonia emissions when using wind tunnels. The differences in the volatilisation rates can be attributed to the environmental variability, leaching, plant uptake, as well as other field processes that are absent under controlled laboratory conditions.

The fertiliser type had the most pronounced effect on the nitrogen loss ($F=2550.18$; $p<0.001$). The mean cumulative losses were highest for white urea (43.99%), followed by carbon-coated urea (30.97%), ammonium nitrate (25.09%) and urease-inhibited urea (8.73%). The control treatments consistently showed minimal losses (0.34%).

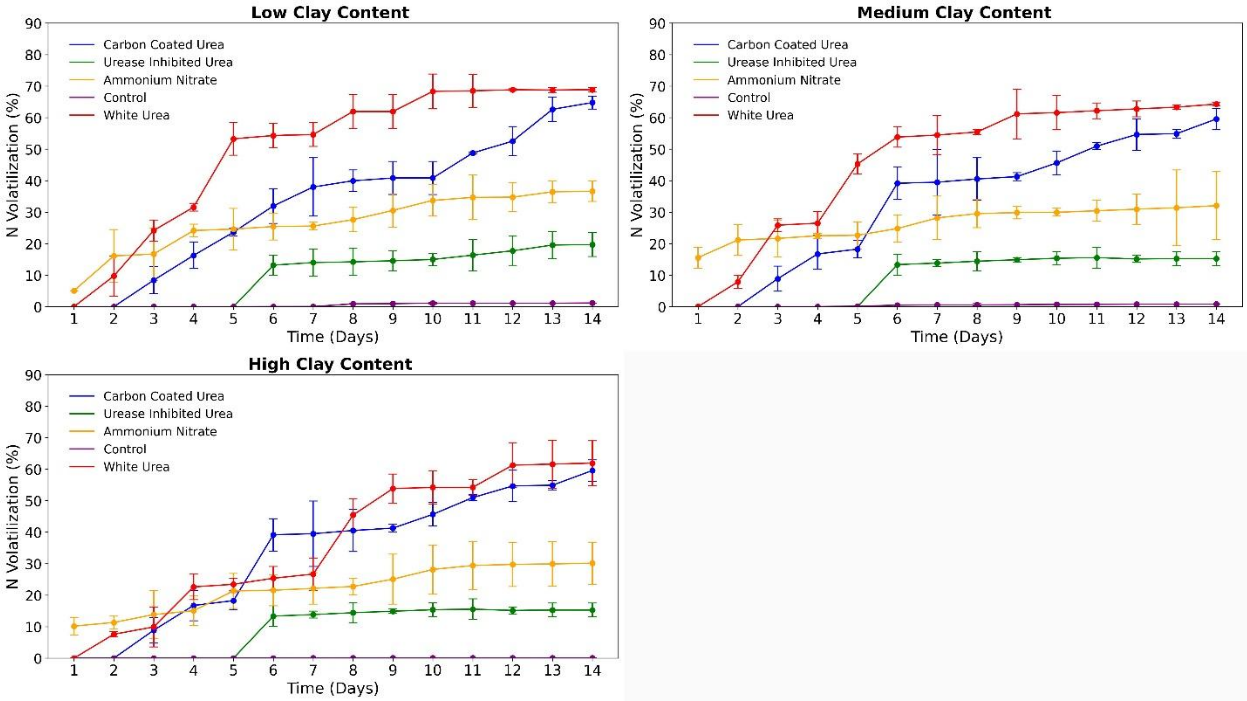

Figure 4. Volatilisation (%) of fertilisers over 14 days in soils with a low-, medium- and high-clay content

A significant interaction between the fertiliser type and clay content (F=18.42; p<0.001) further emphasised the role of the soil texture. White urea losses were highest under all conditions. Similar trends were observed for carbon-coated urea. Urease-inhibited urea consistently showed lower losses across all textures (14-19%). Control treatments remained stable, with negligible losses (Figure 4).

This interaction underscores the importance of matching the fertiliser type to specific soil characteristics. Stabilised fertilisers, like urease-inhibited urea, are particularly effective in reducing nitrogen losses in both alkaline and coarse-textured soils, where uncoated urea products would otherwise lead to significant inefficiencies.

Conclusion and Recommendations

Nitrogen loss through ammonia volatilisation was strongly influenced by the soil pH, the clay content and the fertiliser type. The losses were highest in alkaline soils and in soils with a low clay content. White urea consistently showed the highest volatilisation, while urease-inhibited urea recorded the lowest losses across all conditions. The use of stabilised fertilisers, such as urease-inhibited urea, can significantly reduce the nitrogen losses, especially in high-pH or sandy soils.

It is recommended that fertiliser selection be guided by the soil properties, in order to improve their nitrogen-use efficiency. Avoiding the surface application of untreated urea on alkaline or coarse-textured soils can help to minimise the losses. These findings offer a practical basis for improving the fertiliser recommendations and for guiding nitrogen management in sugarcane production. Future studies must look at the effects of temperature and moisture, as they have not been included in this study (kept constant).

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