

4.5 Flesh quality and welfare implications

The effects of the extracts on flesh quality, as presented in Table 8, provide important insight into post exposure physiological condition. The relatively stable values observed under milder treatments suggest limited metabolic disturbance, which is consistent with the antioxidant properties of citrus derived compounds that help preserve tissue integrity (Russo et al., 2021; Zahran et al., 2021).

In contrast, the reductions in protein and lipid content observed under more potent treatments indicate increased physiological stress and metabolic disruption. Such changes have been associated with altered biochemical composition and reduced product quality in aquaculture species (Hussain et al., 2021; Zahr et al., 2023).

Welfare indicators presented in Table 10 further reinforce these findings. Rapid recovery of normal swimming and feeding behaviour is widely recognised as a reliable indicator of minimal stress and successful anaesthetic recovery (Mphande et al., 2023). Conversely, delayed or absent feeding recovery reflects prolonged physiological disturbance and reduced welfare status (Macaulay et al., 2021; Martos Sitcha et al., 2020). These observations underscore the importance of selecting anaesthetic agents that balance efficacy with welfare considerations.

4.6 Practical implications and study limitations

The cost analysis presented in Table 9 indicates that citrus leaf extracts offer a comparatively economical alternative to conventional anaesthetic agents under local conditions. This finding supports the growing interest in plant based anaesthetics as sustainable and accessible options for aquaculture (Maqbool et al., 2023; Šafranko et al., 2023).

However, the variability in phytochemical composition observed in Table 1 highlights a key limitation for practical application. The concentration and activity of bioactive compounds can vary depending on plant species, environmental conditions, and extraction methods, which may affect consistency and reproducibility (Indriyani et al., 2023). In addition, the relatively small sample size used in this study limits the statistical robustness of the findings, and the results should therefore be interpreted as indicative rather than conclusive.

The combined evidence from Table 1, Table 2, Table 3, Table 4, Table 5, Table 6, Table 7, Table 8, Table 9 and Table 10, as well as Figure 1, Figure 2 and Figure 3, demonstrates that citrus leaf extracts exhibit distinct anaesthetic profiles that are strongly influenced by their phytochemical composition. Extracts rich in volatile compounds provide greater anaesthetic potency but are associated with reduced safety margins, whereas those dominated by antioxidant compounds offer more controlled and safer sedation. The findings also confirm that species specific physiological characteristics significantly influence anaesthetic response, reinforcing the need for tailored application in aquaculture practice.

5 Conclusion

This study provides empirical evidence that citrus leaf extracts possess functional anaesthetic properties and can serve as plant based alternatives to synthetic agents in freshwater aquaculture. By integrating phytochemical composition (Table 1) with behavioural responses (Table 2, Table 3), recovery dynamics (Figure 3 and Table 5), and mortality outcomes (Table 4), the study demonstrates that anaesthetic performance is governed by the balance between neuroactive and protective compounds.

The findings extend existing knowledge by identifying citrus leaves as an underutilised source of bioactive compounds with practical relevance for fish anaesthesia. Unlike previous studies that have focused primarily on established essential oils, this research provides new insight into the role of citrus leaf extracts in modulating anaesthetic response.

The study also highlights the importance of species specific physiology, as demonstrated by the differing responses of *Clarias gariepinus* and *Oreochromis niloticus* across multiple indicators, including behavioural response, recovery, and welfare outcomes (Table 2, Table 3, Table 10). This reinforces the need for species appropriate anaesthetic protocols.