

# Microencapsulation with Maltodextrin and Lecithin Enhances the Stability of Ferric Pyrophosphate

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## Abstract

**Background:** Dietary minerals such as iron, zinc, and calcium must be delivered in bioavailable yet chemically stable forms to prevent mineral-catalyzed oxidation, off-flavors, and discoloration in fortified products. Although iron supplementation is central to managing iron deficiency anemia, the oxidative stability of the selected iron compound critically influences its functional performance. Ferric pyrophosphate (FePP) is widely utilized but remains susceptible to oxidative degradation. Microencapsulation with maltodextrin and lecithin has been proposed to enhance FePP stability; however, comparative data on coated versus uncoated FePP remains limited, warranting systematic investigation.

**Methods:** This study compared the oxidative stability of uncoated FePP and microencapsulated SunActive Fe (coated with maltodextrin and lecithin). Samples were exposed to hydrogen peroxide (0.1%, 1%, 2%, and 3%) to induce oxidative stress. The reduction of ferric (Fe<sup>3+</sup>) to ferrous (Fe<sup>2+</sup>) iron was quantified using a colorimetric assay based on Fe<sup>2+</sup>-1,10-phenanthroline complex formation, measured spectrophotometrically at 510 nm across multiple time points up to 15 minutes.

**Results:** Uncoated FePP demonstrated a rapid, concentration-dependent increase in Fe<sup>2+</sup> levels, indicating high oxidative reactivity. In contrast, microencapsulated SunActive Fe showed significantly lower Fe<sup>3+</sup>→Fe<sup>2+</sup> conversion across all peroxide concentrations and time points ( $p < 0.005$ ), confirming that encapsulation effectively shields ferric centers from peroxide-induced reduction. Furthermore, the ability of microencapsulated FePP to fully interact with the phenanthroline reagent, producing the same Fe<sup>2+</sup>-phenanthroline complex as uncoated FePP, demonstrates that microencapsulation does not alter the intrinsic chemical nature of FePP.

**Discussion:** Microencapsulation with maltodextrin and lecithin enhances the oxidative stability of ferric pyrophosphate by restricting peroxide access and reducing redox cycling. These findings highlight the potential of encapsulation as a simple, cost-effective strategy to improve the stability, safety, and shelf life of iron supplements, particularly under oxidative storage conditions.

**Key words:** Stability, Iron, Maltodextrin, Lecithin, Ferric pyrophosphate, Supplement, Storage

## INTRODUCTION

Minerals are vital micronutrients required by the human body to regulate physiological processes, maintain structural integrity, and support enzymatic functions essential for health and metabolism.<sup>[1]</sup> Iron is an essential trace mineral widely used in pharmaceutical and nutraceutical supplements for the prevention and treatment of iron deficiency anemia (IDA). It plays a

critical role in various biological processes, including oxygen transport as a key component of hemoglobin, as well as in energy metabolism, immune system function, and DNA synthesis. In dietary and therapeutic formulations, iron is predominantly administered in two oxidation states: The ferrous (Fe<sup>2+</sup>) and ferric (Fe<sup>3+</sup>) forms. The selection of an appropriate iron salt depends on multiple factors such as bioavailability, gastrointestinal tolerability, oxidative reactivity, and overall formulation stability. Given the widespread use of iron in oral supplementation, it is essential to ensure that the iron being used is stable and not oxidized. With this in mind, several encapsulated irons have been introduced, the most popular of which use a ferric pyrophosphate salt that is encapsulated with maltodextrin and lecithin as anti-dusting agents, stabilizers, carriers, or agents to help

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preserve during storage and transport. However, their role in a head-to-head comparison against unencapsulated ferric pyrophosphate has not been examined.<sup>[2]</sup>

Maltodextrin, a starch-derived polysaccharide, serves as an inert and versatile excipient in microencapsulated ferric pyrophosphate systems. In spray-drying processes, it plays a critical role as a film-former and matrix-building agent, creating a protective carbohydrate shell around iron particles. This matrix not only stabilizes ferric pyrophosphate during processing but also helps control particle morphology, reduce hygroscopicity, and improve overall powder flow.<sup>[3]</sup> As a bulking agent, it increases powder volume without significantly altering taste or caloric density, minimizes dusting, and enhances dispersion in beverages and food matrices. These properties are essential for developing consumer-friendly iron-fortification products, while also supporting precise dosing and maintaining formulation homogeneity in nutraceutical tablets, capsules, and dry mixes.<sup>[4,5]</sup>

Lecithin, a phospholipid-rich emulsifier, plays a complementary role by aiding dispersion of poorly water-soluble ferric pyrophosphate particles at aqueous interfaces and promoting formation of stable colloidal or microcapsule structures when combined with carbohydrate carriers such as maltodextrin. Its amphiphilic nature allows lecithin to adsorb at particle and droplet surfaces, improving wetting, dispersion, and interfacial stabilization in liquid systems. In addition, lecithin has been shown in emulsion models to influence oxidative processes at interfaces, partly through its interfacial organization and the intrinsic antioxidant-like effects of certain phospholipid components, which can affect radical access and propagation near the encapsulated phase.<sup>[6]</sup>

### Reductive Conversion of Ferric Pyrophosphate by Hydrogen Peroxide

While ferric iron ( $\text{Fe}^{3+}$ ) represents the most oxidized and thermodynamically stable form of iron in both aqueous and physiological systems, it can nonetheless undergo reduction to ferrous iron ( $\text{Fe}^{2+}$ ) under certain environmental or chemical conditions. This redox transformation is especially relevant in the context of iron-containing formulations such as ferric pyrophosphate. Despite being in an oxidized state, ferric iron, when exposed to oxidizing agents like hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), can paradoxically be reduced to ferrous iron rather than undergoing further oxidation. This counterintuitive redox behavior underscores the complex chemistry of iron and has significant implications for oxidative stability in food, pharmaceutical, and nutraceutical systems.<sup>[7]</sup>

Hydrogen peroxide is a bifunctional redox molecule with the capacity to act both as an oxidizing and reducing agent. Its specific reactivity is determined by the redox

potential and the coordination environment of the metal ion in question. In the classical Fenton reaction, ferrous iron ( $\text{Fe}^{2+}$ ) reacts with  $\text{H}_2\text{O}_2$ , resulting in its oxidation to ferric iron ( $\text{Fe}^{3+}$ ) and the concurrent generation of highly reactive hydroxyl radicals ( $\cdot\text{OH}$ ), as illustrated in the following reaction:



However, under certain conditions, the reverse process can also occur. In what is known as the Haber-Weiss variant of the Fenton reaction, ferric iron ( $\text{Fe}^{3+}$ ) is reduced back to ferrous iron ( $\text{Fe}^{2+}$ ) in the presence of hydrogen peroxide, producing hydroperoxyl radicals ( $\cdot\text{HO}_2$ ) and protons ( $\text{H}^+$ ):



This reduction pathway becomes particularly significant in formulations containing ferric pyrophosphate, where  $\text{Fe}^{3+}$  is loosely complexed with pyrophosphate ligands. While pyrophosphate acts as a chelating agent and helps to stabilize ferric iron, it does not fully inhibit redox cycling, especially under oxidative stress. On exposure to hydrogen peroxide, partial dissociation of the  $\text{Fe}^{3+}$ -pyrophosphate complex can occur. This dissociation allows  $\text{Fe}^{3+}$  to become chemically available and susceptible to reduction. The newly formed  $\text{Fe}^{2+}$  is both more soluble and more reactive than its ferric counterpart, and in the continued presence of  $\text{H}_2\text{O}_2$ , it can drive further Fenton-type reactions, leading to a cascade of oxidative events.<sup>[8,9]</sup>

This redox conversion of  $\text{Fe}^{3+}$  to  $\text{Fe}^{2+}$  is not merely a theoretical concern – it holds practical importance in both analytical assays and formulation design. In laboratory settings, this reaction serves as an indirect measure of oxidative instability. A widely used analytical approach involves the addition of 1,10-phenanthroline, a selective chelating agent for  $\text{Fe}^{2+}$ . This compound forms a stable, red-orange tris-complex ( $[\text{Fe}(\text{phen})_3]^{2+}$ ) with ferrous iron, which exhibits a characteristic absorbance at 510 nm. By measuring the increase in absorbance following  $\text{H}_2\text{O}_2$  treatment, researchers can quantitatively assess the extent of  $\text{Fe}^{3+}$  reduction and, by extension, the oxidative reactivity of the iron-containing formulation.

The present study aimed to evaluate the oxidative stability of two ferric pyrophosphate formulations, uncoated Generic Ferric Pyrophosphate and encapsulated SunActive Fe, by quantifying  $\text{Fe}^{2+}$  generation in the presence of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) using the 1,10-phenanthroline assay. SunActive Fe is a commercially available preparation in which ferric pyrophosphate is microencapsulated with maltodextrin and lecithin, functioning as antidusting agents, stabilizers and carriers. The results demonstrated

that the encapsulated formulation exhibited significantly lower  $\text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$  conversion compared to the uncoated variant across all tested  $\text{H}_2\text{O}_2$  concentrations and time points. This suggests that the encapsulating matrix confers protective effects against reductive degradation by limiting the accessibility of ferric ions to oxidative agents. The improved resistance to reduction indicates enhanced oxidative stability, which may have important implications for the formulation's shelf-life, bioavailability, and suitability in oxidative environments.

## MATERIALS AND METHODS

### Chemicals and Reagents

Analytical-grade reagents were used for all experiments. 1,10-Phenanthroline monohydrate (0.1% w/v), hydroxylamine hydrochloride (10% w/v), and sodium acetate (10% w/v) were prepared in distilled water. A ferrous ammonium sulfate standard solution was prepared by dissolving 0.07 g of salt in distilled water, followed by the addition of 2.5 mL of concentrated sulfuric acid, and the volume was adjusted to 1 L (final concentration: 0.07 mg  $\text{Fe}^{2+}$ /mL). Ferric chloride ( $\text{FeCl}_3$ ) and ferrous sulfate ( $\text{FeSO}_4$ ) were used as positive controls for  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$ , respectively. Hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) solutions were freshly prepared in four concentrations: 0.1%, 1%, 2%, and 3% (v/v in deionized water).

### Samples

Two iron test samples were evaluated: Coated ferric pyrophosphate (FePP) and uncoated FePP. Control samples included  $\text{FeSO}_4$ ,  $\text{FeCl}_3$ , and blank solutions. For all tests, iron solutions were prepared by dispersing 1 g of FePP in 100 mL of deionized water and sonicated briefly to ensure uniformity.

### Instrumentation and Glassware

Standard laboratory glassware was used, including 100 mL and 250 mL beakers, conical flasks, volumetric flasks, and test tubes. Transfers were made using pipettes and micropipettes (with tips). A ultraviolet (UV)-visible spectrophotometer was employed to measure absorbance at 510 nm. A probe sonicator was used for suspension of FePP powders.

### Preparation of Control Solutions

Control solutions were prepared to establish baselines and assess interferences. The composition of each 5 mL control is described in Table 1.

### Iron Oxidation Testing Procedure

The redox behavior of ferric iron was assessed using a colorimetric method based on  $\text{Fe}^{2+}$ -1,10-phenanthroline complexation. For each test sample, the following reagents were added to a 100 mL volumetric flask in sequence: 2.5 mL iron solution (coated or uncoated FePP), 2.5 mL  $\text{H}_2\text{O}_2$  (at desired concentration), 1 mL hydroxylamine hydrochloride, 10 mL 1,10-phenanthroline solution, and 8 mL sodium acetate solution.

The mixture was diluted to volume with deionized water. The solution was mixed thoroughly, and the absorbance was recorded at 510 nm using a UV-visible spectrophotometer at 5 time points: 0 s, 5 s, 1 min, 5 min, and 15 min.

### Control Testing Procedure

Control solutions (5 mL) were treated similarly by adding 1 mL hydroxylamine, 10 mL 1,10-phenanthroline, and 8 mL sodium acetate, followed by dilution to 100 mL. Absorbance at 510 nm was recorded. If absorbance values exceeded 1.0, the solution was diluted (1:10) to remain within the linear detection range.

## RESULT

### Effect of $\text{H}_2\text{O}_2$ on Iron Stability

The oxidation behavior of coated and uncoated FePP was evaluated across four concentrations of hydrogen peroxide (0.1%, 1%, 2%, and 3%) and at 5 time points (0 s, 5 s, 1 min, 5 min, 15 min). The generation of  $\text{Fe}^{2+}$ , as indicated by increasing absorbance at 510 nm, was used as a measure of  $\text{Fe}^{3+}$  reduction, reflecting iron redox activity under oxidative stress [Table 2].

Uncoated FePP demonstrated a rapid, concentration-dependent increase in  $\text{Fe}^{2+}$  levels, indicating high oxidative reactivity. In contrast, microencapsulated SunActive Fe showed significantly lower  $\text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$  conversion across all peroxide concentrations and time points ( $p < 0.005$ ), confirming that encapsulation effectively shields ferric

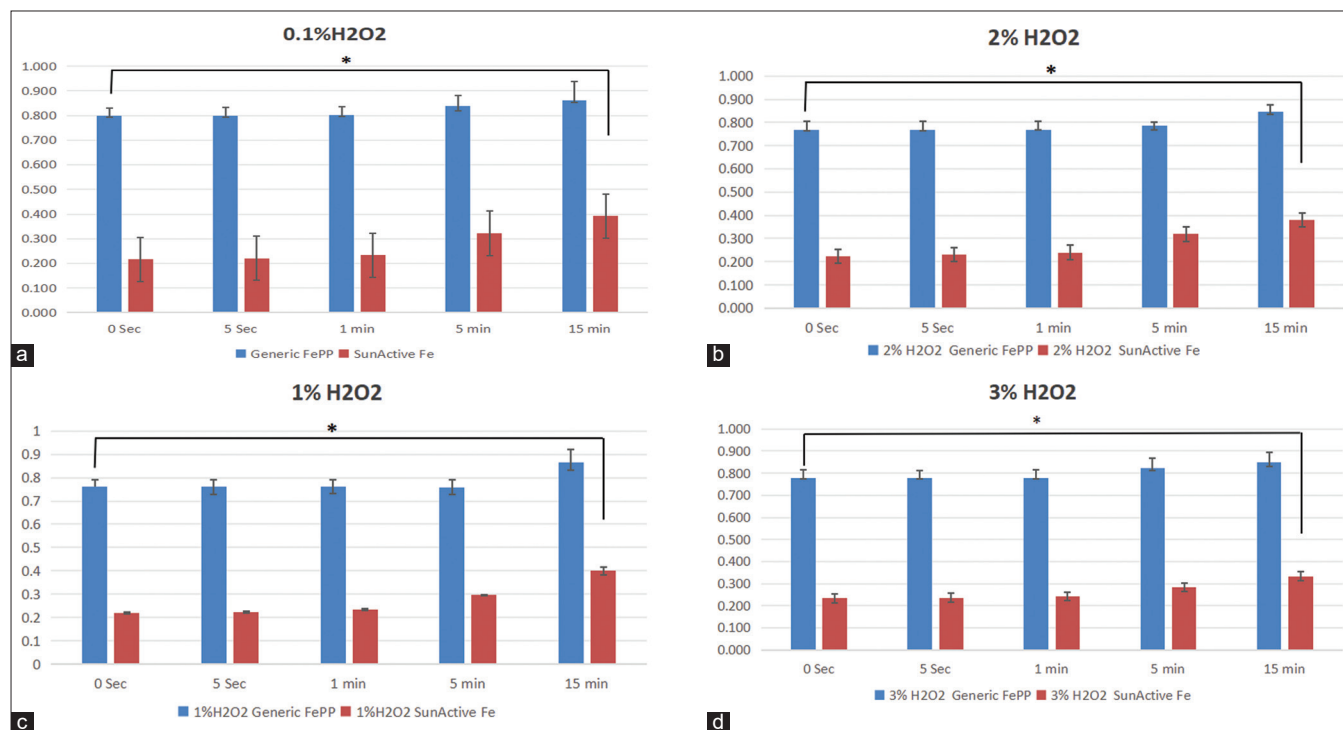
**Table 1: Composition of control solutions**

Control type	$\text{H}_2\text{O}_2$ (mL)	Test sample (mL)	$\text{FeCl}_3$ (mL)	$\text{FeSO}_4$ (mL)	Deionized water (mL)	Total volume (mL)
Blank	–	–	–	–	5.0	5.0
$\text{H}_2\text{O}_2$ control	2.5	–	–	–	2.5	5.0
Negative control	–	2.5	–	–	2.5	5.0
$\text{Fe}^{2+}$ positive control	–	–	–	2.5	2.5	5.0
$\text{Fe}^{3+}$ positive control	–	2.5	2.5	–	–	5.0

**Table 2: Effect of hydrogen peroxide on Fe<sup>3+</sup> → Fe<sup>2+</sup> conversion in Generic FePP and SunActive™ Fe measured by absorbance at 510 nm (Phenanthroline assay)**

Time	0.1% H <sub>2</sub> O <sub>2</sub>			1% H <sub>2</sub> O <sub>2</sub>			2% H <sub>2</sub> O <sub>2</sub>			3% H <sub>2</sub> O <sub>2</sub>		
	Sunactive Fe	Generic FePP	P-value	Sunactive Fe	Generic FePP	P-value	Sunactive Fe	Generic FePP	P-value	Sunactive Fe	Generic FePP	P-value
0 s	0.216	0.799	0.0001	0.219	0.761	0.0001	0.223	0.769	0.00012	0.233	0.780	0.0001
5 s	0.221	0.799	0.0001	0.223	0.760	0.0001	0.230	0.767	0.00013	0.236	0.778	0.0001
1 min	0.233	0.803	0.0001	0.233	0.761	0.0001	0.240	0.769	0.00013	0.242	0.779	0.0001
5 min	0.322	0.839	0.0003	0.297	0.756	0.0002	0.319	0.787	0.00004	0.283	0.822	0.0003
15 min	0.392	0.862	0.0038	0.401	0.867	0.0012	0.379	0.847	0.00014	0.334	0.847	0.0005

FePP: Ferric pyrophosphate



**Figure 1: (a-d): Comparative Fe<sup>2+</sup> generation in Generic FePP and SunActive Fe at increasing concentrations of hydrogen peroxide (0.1%, 1%, 2%, and 3%). Across all peroxide levels and time points, uncoated FePP showed rapid and concentration-dependent Fe<sup>3+</sup> → Fe<sup>2+</sup> conversion, whereas SunActive Fe consistently demonstrated significantly lower absorbance values, confirming superior oxidative stability conferred by microencapsulation.**

centers from peroxide-induced reduction. Furthermore, the ability of microencapsulated FePP to fully interact with the phenanthroline reagent, producing the same Fe<sup>2+</sup>-phenanthroline complex as uncoated FePP, demonstrates that microencapsulation does not alter the intrinsic chemical nature of FePP [Figure 1 (a-d)].

### Comparative Redox Stability

When comparing both test materials, the coated FePP consistently demonstrated superior oxidative stability under peroxide challenge. At 3% H<sub>2</sub>O<sub>2</sub> and 15 min, the absorbance of the uncoated FePP group was markedly higher than that of the coated variant, confirming that

the protective coating effectively mitigated oxidative degradation.

### Control Experiments

Control assays with FeSO<sub>4</sub> (positive Fe<sup>2+</sup> control) and FeCl<sub>3</sub> (positive Fe<sup>3+</sup> control) validated the specificity of the detection method. The FeSO<sub>4</sub> solution yielded high absorbance at 510 nm, consistent with its reduced iron content, whereas FeCl<sub>3</sub> showed minimal signal in the absence of reductants. The negative and reagent controls confirmed that H<sub>2</sub>O<sub>2</sub> alone or test medium components did not generate interfering absorbance. All blank and diluted samples remained within acceptable spectrophotometric limits (absorbance <1.0).

## DISCUSSION

The present study demonstrates that SunActive Fe, an encapsulated FePP formulation, exhibits markedly superior oxidative stability compared to uncoated FePP when challenged with hydrogen peroxide. The encapsulated preparation consistently showed lower  $\text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$  conversion across all  $\text{H}_2\text{O}_2$  concentrations and time points, supporting the hypothesis that the lecithin–maltodextrin coating functions as a physical and chemical barrier, thereby restricting peroxide accessibility to ferric centers.

The reduction of  $\text{Fe}^{3+}$  to  $\text{Fe}^{2+}$  by  $\text{H}_2\text{O}_2$  observed in uncoated FePP aligns with the mechanistic principles of the Haber–Weiss variant of the Fenton reaction, wherein ferric ions are reduced by hydrogen peroxide to ferrous ions, generating hydroperoxyl radicals ( $\bullet\text{HO}_2$ ).<sup>[10]</sup> This reaction is facilitated when  $\text{Fe}^{3+}$  is loosely complexed, as in the pyrophosphate matrix, which does not fully inhibit ligand exchange under oxidative stress. The higher reactivity and solubility of the  $\text{Fe}^{2+}$  thus generated can promote further redox cycling and oxidative damage in formulations.

The encapsulation of ferric salts in food and nutraceutical matrices has been shown to mitigate oxidative degradation by physically shielding the iron from pro-oxidants and by modulating its local microenvironment.<sup>[11]</sup> Lecithin, owing to its amphiphilic phospholipid structure, forms a hydrophobic interfacial layer around FePP particles, thereby reducing their direct exposure to aqueous oxidants. Maltodextrin complements this effect by serving as a carrier and matrix-forming agent that limits peroxide accessibility while simultaneously providing bulk to the formulation. Its bulking properties improve powder flow, reduce dusting, and minimize airborne particulate formation, enhancing handling and processing efficiency.<sup>[12]</sup>

Beyond its structural role, maltodextrin is a partially hydrolyzed starch widely used to encapsulate food ingredients, nutraceuticals, essential oils, and other sensitive actives. Maltodextrin-based microcapsules are known to improve the solubility, dispersibility, and stability of core materials by protecting them from degradation induced by heat, oxygen, and moisture.<sup>[13]</sup> It has also been documented as a stabilizer for Vitamin C, effectively reducing oxidative losses.<sup>[14]</sup> These functionalities align with the reduced  $\text{Fe}^{2+}$  formation observed in encapsulated SunActive Fe, where maltodextrin facilitates efficient spray-drying and creates a protective matrix that enhances both processing stability and shelf life. Together, maltodextrin and lecithin coatings improve thermal stability, color properties, and overall robustness of microencapsulated systems, supporting their suitability for commercial applications in food, cosmetic, and pharmaceutical formulations.<sup>[15]</sup>

Furthermore, oxidative instability of unprotected FePP has been previously reported to compromise both shelf life and bioavailability, underscoring the importance of protective delivery systems in commercial formulations. The findings of this study expand on these observations by providing direct quantitative evidence. Through the phenanthroline assay, microencapsulation significantly suppresses peroxide-driven  $\text{Fe}^{3+}$  reduction.

From a formulation perspective, this stability advantage has critical implications. Since iron supplements are rarely packaged under inert atmospheres and are thus continuously exposed to oxygen, incorporating encapsulation could enhance transport stability, reduce nutrient loss during storage, and improve consumer safety by limiting unintended oxidative reactions.

## CONCLUSION

This study demonstrates that SunActive Fe (coated FePP) shows significantly higher oxidative stability compared to uncoated FePP when exposed to hydrogen peroxide. The uncoated FePP exhibited rapid  $\text{Fe}^{3+}$  to  $\text{Fe}^{2+}$  conversion, indicating poor stability under oxidative stress. In contrast, SunActive Fe resisted reduction across all  $\text{H}_2\text{O}_2$  concentrations and time points, confirming that its coating effectively protects iron from oxidative degradation. These results are the first to corroborate the hypothesis that encapsulating iron, and ferric salts in particular, with maltodextrin and lecithin will protect against oxidative stress. Given that iron salts are not routinely packed in nitrogen-filled environments, they are consistently exposed to oxygen. As per our results, encapsulation presents a viable and attractive alternative for transport stability and to increase the shelf life of ferric salts.

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## AUTHOR CONTRIBUTIONS STATEMENT

The Author conceived and designed the study, conducted the experiments, analyzed the results, and prepared the manuscript. All authors reviewed and approved the final version of the manuscript.

## ADDITIONAL INFORMATION

### Conflicts of Interest

The author is neither affiliated with nor financially recompensed by any company or organization.

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### Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. All tested samples were procured from the market since they are commercially available products. Testing was carried out at an independent NABL-accredited lab.

### Ethics Approval and Consent to Participate

Not applicable.

### Consent for Publication

All authors have read and approved the final version of the manuscript and consent to its publication.

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