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Review Article

Acids, Bases, and Indicators: Unveiling the Science Behind Colourful Chemistry

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ABSTRACT

Acid-base indicators play a crucial role in chemical analysis, industry, and everyday applications. These substances change color in response to pH variations, making them valuable tools for identifying acids and bases. This review explores the nature of indicators, their types, theories explaining their behavior, and their wide-ranging applications in various fields, including pharmaceuticals, food industries, and environmental monitoring.

INTRODUCTION

Acid-base indicators are essential tools in chemical analysis, used to determine the acidity or basicity of a solution by undergoing distinct color changes at specific pH levels.1 These indicators are either weak acids or weak bases that exhibit different colors in their protonated and deprotonated forms, making them invaluable in laboratory experiments, pharmaceutical formulations, and industrial applications.2 In chemical analysis, precise identification of pH is crucial for various applications, including drug formulation, quality control, and titration experiments. Indicators provide a quick and cost-effective method to assess pH changes without the need for sophisticated instruments. They are widely used in pharmaceuticals to ensure drug stability, in food industries for quality control, and even in environmental monitoring to detect

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pollution levels.3. Acid-base indicators function based on the principles of chemical equilibrium. When an indicator is added to a solution, it establishes an equilibrium between its acid and base forms. As the pH of the solution changes, the ratio of these forms shifts, leading to a visible color transition. For instance, phenolphthalein turns pink in basic solutions but remains colorless in acidic conditions, making it a popular choice for titrations.4 Similarly, litmus changes from red in acidic solutions to blue in basic solutions, offering a simple yet effective way to test pH. Beyond these classical indicators, the concept of olfactory indicators adds an intriguing dimension to acid-base analysis.5 Certain substances, like vanilla or onion extract, change their smell in acidic and basic conditions, providing an alternative sensory approach to pH detection. The study of acid-base indicators is deeply rooted in the theories of acid-base chemistry, including Arrhenius, Brønsted-Lowry, and Lewis theories, which explain how acids and bases interact with these indicators.6 Their versatility extends beyond the laboratory, playing a significant role in medical diagnostics, pharmaceuticals, and industrial applications. This article delves into the fascinating world of acid-base indicators, exploring their classification, mechanisms, and real-world applications, offering insights that are essential for both undergraduate and postgraduate pharmacy students.

Classification of Indicators

1. **Natural Indicators:** These are derived from plant sources and change color based on the pH of the solution.[7,8] For example, Litmus, extracted from lichens, turns red in acidic solutions and blue in basic solutions, making it a classic pH indicator used in laboratories. Turmeric, a kitchen staple, remains yellow in acidic conditions but turns reddish-brown in basic environments, commonly observed when soap comes in contact with turmeric stains. Red cabbage extract is a natural, eco-friendly pH indicator that changes color based on acidity or basicity due to anthocyanins. It turns reddish-pink in acids, purple in neutral solutions, and green to yellow in bases.

2. **Synthetic Indicators:** These are laboratory-prepared compounds with distinct and sharp color changes at specific pH ranges.[8] Example: Phenolphthalein is colorless in acidic solutions but turns pink in basic solutions, making it widely used in titrations involving strong bases like sodium hydroxide. Methyl orange shifts from red in acidic conditions to yellow in basic solutions, making it useful in detecting endpoint transitions in acid-base titrations.

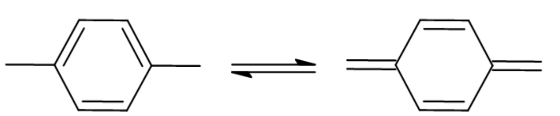
3. **Olfactory Indicators:** These indicators work by altering their smell rather than their color in acidic or basic environments.[8] Example: Onion extract loses its pungent smell in basic solutions but retains it in acidic conditions, offering a unique way to detect pH changes. Vanilla essence loses its characteristic sweet aroma in alkaline solutions, making it another unconventional but effective acid-base indicator. Clove loses its characteristic smell in basic solutions but retains it in acidic conditions, making it an effective olfactory indicator.

6. Theories of Acid-Base Indicators

Ostwald's Theory: As per Ostwald's theory, acid-base indicators work using the concept of ionization and color change.[9,10] According to this theory, indicators are typically weak acids or weak bases that exist in equilibrium between their ionized and unionized forms. The unionized form (HIn) and its ionized form (In^-) have different colors. The color change usually occurs at a particular pH, known as the $_pKa$ of the indicator.

- In acidic solutions: Hin ⇌ H^++In− Excess H^+ shifts the equilibrium left, showing the colour of HIn.
- In basic solutions: InOH ⇌ In^+ + OH^- Excess OH^- shifts the equilibrium right, showing the color of In^+.
- For example, phenolphthalein is colorless in acidic medium (unionized form) and pink in basic medium (ionized form). Methyl Orange is red in acidic medium and yellow in basic medium.

Quinonoid Theory: According to this theory, the color change is due to the structural transformation of the indicator molecule, specifically the formation of a quinonoid structure.[9,10] The Quinonoid theory provides a structural explanation for indicator color changes by highlighting the shift between benzenoid and quinonoid forms. This theory complements Ostwald's theory by adding a molecular perspective.



As per this theory, acid-base indicators exist in two tautomeric forms- Benzenoid form is often colorless or lightly colored and Quinonoid form is intensely colored. When the pH changes, the structure shifts between the benzenoid and quinonoid form. The quinonoid form has a conjugated double-bond system, which absorbs visible light, resulting in a color change. In an acidic medium, the indicator may predominantly exist in the benzenoid form, while in a basic medium, it may shift to the quinonoid form. For example, Phenolphthalein Benzenoid form is Colorless in acidic medium, while its Quinonoid form is pink in basic medium. The quinonoid form of Methyl Orange is red in acidic medium, while its benzenoid form is yellow in basic medium.

7. Applications of Indicators

A. Daily Life

Acid-base indicators are not just for laboratories, they play a significant role in various aspects of our daily lives.[11-13] Indicators are practical tools that simplify decision-making in homes, agriculture, healthcare, and environmental monitoring. Details were provided in Table 1.

Table 1. Applications of indicators in daily life

S. No.	Areas of life	Applications
1	Household Products	• Litmus Paper: Used to test the acidity or alkalinity of cleaning products like detergents and soaps. • Baking Soda Test: Vinegar and baking soda produce bubbles, indicating a reaction with an acid.
2	Agriculture	• Soil Testing: Farmers use indicators to check soil pH, ensuring it's suitable for crop growth. • Lime Treatment: If soil is too acidic, lime is added to neutralize it.
3	Food and Beverages	• Freshness Check: Spoiled food often becomes acidic, which can be tested using indicators. • Cabbage Juice Indicator: Red cabbage extract is a natural pH indicator that turns red in acids and green in bases.

4	Healthcare	• Urine and Saliva Tests: pH test strips are used to monitor health conditions. • Antacid Effectiveness: Indicators confirm if antacids neutralize excess stomach acid.
5	Environmental Monitoring	• Water Quality Testing: Indicators detect acidic pollution in water bodies. • Acid Rain Analysis: Rainwater pH levels are checked to monitor environmental health.

B. Identification of Chemicals

Indicators are widely used to identify chemicals, particularly acids, bases, and neutral substances. They help detect the nature of a substance by showing a visible color change when added to a solution.[8,9] Indicators offer a quick and reliable way to identify acids, bases, and neutral substances. Whether in labs, industries, or homes, they make chemical detection simple and effective (**Table 2**).

Table 2. Applications of indicators in identifying chemicals

Litmus Paper • Blue Litmus Paper: Turns red when exposed to an acid. • Red Litmus Paper: Turns blue when in contact with a base. • No Color Change: Indicates a neutral substance. **Example:** Testing lemon juice (acidic) and soap solution (basic).	**Universal Indicator** • A universal indicator provides a spectrum of colors based on the pH value. • Red to Yellow: Strong to weak acids (pH 1-6). • Green: Neutral (pH 7). • Blue to Purple: Weak to strong bases (pH 8-14). **Example:** Identifying vinegar (acid) and baking soda solution (base).
Phenolphthalein • Colourless in acidic solutions. • Pink in basic solutions. **Example:** Confirming the presence of sodium hydroxide by observing a pink hue.	**Methyl Orange** • Red in acidic solutions. • Yellow in basic solutions. **Example:** Checking for acid contamination in drinking water.

C. Food Industry

Indicators play a crucial role in the food industry to monitor quality, safety, and freshness. From detecting spoilage to ensuring pH balance, they provide quick and reliable results.[12, 14] From ensuring safety to enhancing product quality, indicators are essential in the food industry (**Table 3**). They offer a simple yet effective way to maintain consumer trust and satisfaction.

Table 3. Applications of indicators in Food Industry

S. No.	Areas of Food Industry	Applications
1	Freshness and Spoilage Detection	• pH Indicators: Used to check the freshness of meat, seafood, and dairy products. A drop in pH often signals spoilage. • Color Change Indicators: Smart packaging contains sensors that change color if food has gone bad. Example: Fresh fish packaging often uses indicators to detect ammonia from spoilage.
2	Monitoring Fermentation	• Fermented foods like yogurt, cheese, and pickles rely on precise pH levels. • Litmus Paper or pH Meters: Used to track the acidity during fermentation. Example: Yogurt production uses pH indicators to ensure the desired tangy flavor.
3	Quality Control in Beverages	• Phenolphthalein and Methyl Orange: Used to ensure proper acidity or alkalinity in soft drinks, juices, and alcoholic beverages. Example: Wine producers monitor pH during fermentation to maintain flavor consistency.
4	Food Preservation	• Indicators in packaging detect oxygen exposure, ensuring sealed products remain fresh. Example: Oxygen-sensitive indicators in snack bags ensure the packaging remains airtight.
5	Nutrient and Chemical Analysis	• Indicators are used in laboratories to analyze nutrients and detect contaminants in food samples. Example: Testing for vitamin C levels in juices using iodine as an indicator.

D. Chemical Industry

Indicators play a significant role in the chemical industry by ensuring accurate monitoring, quality control, and safety. They are essential for detecting changes in pH, chemical reactions, and the presence of specific compounds. [15, 16] Whether it's monitoring reactions or detecting pollutants, they keep operations running smoothly (**Table 4**).

Table 4. Applications of indicators in Chemical Industry

S. No.	Areas of Chemical Industry	Applications
1	pH Monitoring in Chemical Reactions	• Acid-Base Indicators: Chemicals like phenolphthalein and methyl orange are used in titrations to determine the endpoint of a reaction. Example: In the production of detergents and pharmaceuticals, pH monitoring ensures product stability.
2	Quality Control and Testing	• Indicators help maintain consistent quality by checking for impurities or verifying chemical compositions. • Example: In petrochemical industries, indicators ensure correct pH levels in coolant systems.
3	Environmental Monitoring	• Colorimetric Indicators: Used for detecting pollutants in air, water, or soil.

		• Example: Industrial effluents are often tested using pH indicators to check for acidic or alkaline waste.
4	Process Safety Management	• Indicators provide early warnings of hazardous conditions by detecting chemical leaks or unstable reactions. • Example: Ammonia or chlorine gas detectors use indicators that change color upon exposure.
5	Corrosion Prevention	• Chemical industries use pH indicators to monitor the acidity of fluids in pipelines and machinery. • Example: In oil refineries, pH indicators help prevent corrosion in storage tanks.

E. Pharmaceutical Industry

In the pharmaceutical industry, indicators play a vital role in quality control, product formulation, and research. They provide visual confirmation of chemical changes, ensuring safety and efficacy in drug development. Indicators ensure pharmaceutical products meet strict safety and quality standards.[17, 18] From formulation to final testing, they're a small but powerful tool in drug manufacturing (**Table 5**).

Table 5. Applications of indicators in Pharmaceutical Industry

S. No.	Areas of Chemical Industry	Applications
1	pH Monitoring and Adjustment	Purpose: Maintain the desired pH in formulations like tablets, syrups, and injections. Example: Phenolphthalein or methyl orange helps adjust pH during buffer preparation to ensure drug stability.
2	Titrations in Drug Analysis	Purpose: Determine the concentration of active pharmaceutical ingredients (APIs). Example: Acid-base titrations use indicators like bromothymol blue for precise endpoint detection.
3	Quality Control and Purity Testing	Purpose: Ensure the chemical purity of raw materials and final products. Example: Colorimetric indicators check for impurities or degradation products.
4	Dissolution Studies	Purpose: Monitor how quickly a drug dissolves, ensuring effective release. Example: pH indicators confirm whether the dissolution medium remains within the specified range.
5	Sterility and Contamination Detection	Purpose: Detect microbial contamination in pharmaceutical products. Example: Special pH indicators detect metabolic byproducts of bacteria, indicating contamination.

F. Other Applications

Apart from their applications in daily life, chemical identification, the food industry, the chemical industry, and the pharmaceutical industry, indicators are used in various other fields. Indicators are versatile tools across multiple industries, providing essential insights for safety, quality, and research purposes.[19-21] Here are some notable applications mentioned under Table 6.

Table 6. Miscellaneous applications of indicators

S. No.	Areas	Applications
1	Environmental Monitoring	Purpose: Detect pollution levels and monitor environmental health. Example: pH indicators are used to test the acidity of water bodies, assessing pollution from industrial waste.
2	Textile Industry	Purpose: Control the pH during fabric dyeing and finishing processes. Example: Litmus and phenolphthalein indicators help maintain the correct pH for dye fixation.
3	Biotechnology and Research	Purpose: Monitor biochemical reactions in labs. Example: Indicators like bromothymol blue are used in cell culture media to detect metabolic changes.
4	Agriculture and Soil Testing	Purpose: Determine soil pH to ensure optimal crop growth. Example: Universal pH indicators guide farmers in adjusting soil pH using fertilizers or lime.
5	Battery and Electrochemical Applications	Purpose: Monitor pH and chemical changes in battery fluids. Example: Indicators ensure proper functioning of acid-based batteries and electrochemical cells.
6	Water Treatment Plants	Purpose: Control pH levels during water purification processes. Example: Methyl orange and phenolphthalein indicate whether the treated water is safe for consumption.
7	Forensic Science	Purpose: Detect biological evidence and chemical substances. Example: pH indicators can identify bloodstains or test for chemical residues at crime scenes.

CONCLUSION

Indicators are invaluable tools in various fields, serving as reliable agents to monitor and measure chemical changes. From detecting acidity and alkalinity to ensuring safety and quality in industries, their applications are vast and impactful. Whether in laboratories, environmental monitoring, agriculture, or healthcare, indicators provide quick, accurate insights that drive informed decision-making. Understanding the role of indicators not only enhances scientific knowledge but also fosters awareness of their significance in our everyday lives. By mastering their applications, students and professionals alike can contribute to advancements in research, sustainability, and public health.

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