

Expected Responses.

May 2026

S6 CHEMISTRY Theory.

Weekly Test II

2 hours.

INSTRUCTIONS

- Attempt all items in this paper
- Write your responses on the answer sheets provided
- Begin response to each item on a fresh page.

Item 1

A leading beverage manufacturing company in Kireka is in a major product reformulation crisis. The company wants to develop a new low-calorie soft drink that maintains the desired sweetness level while minimising production costs and health concerns associated with high sugar content. In the product formulation, they use an amount of the sweetener added to water to make an aqueous solution that has to keep from freezing at -0.33°C as another process is carried out.

They are considering replacing sucrose, $\text{C}_{12}\text{H}_{22}\text{O}_{11}$, with a synthetic sugar substitute labelled T, because supplier advertisement is that it is more stable than most sweeteners on the market such as the sucrose they are currently using.

To make an informed decision, the quality control laboratory conducted combustion analysis on compound T and provided the following eudiometric data from the complete combustion of 0.50 g of T:

- Volume of CO_2 produced = 0.533 dm^3 at s.t.p.
- Volume of N_2 produced = 0.0381 dm^3 at s.t.p.
- Mass of H_2O produced = 0.275g

The company also provided the following additional thermochemical and physical data:

- Standard heat of formation of T = $-1273 \text{ kJ mol}^{-1}$
- Standard heats of combustion: C(graphite) = $-393.5 \text{ kJ mol}^{-1}$, $\text{H}_2(\text{g}) = -285.8 \text{ kJ mol}^{-1}$, Sucrose = $-5640 \text{ kJ mol}^{-1}$
- Cryoscopic constant of water, $K_f = 1.86 \text{ K kg mol}^{-1}$
- Freezing point of pure water = 0.00°C
- Atomic masses: C = 12, H = 1, O = 16, N = 14
- $T = 294.31 \text{ g mol}^{-1}$
- The price of T and sucrose per kilogram on the Ugandan market is the same.

Task:

As a senior chemistry student on internship at the company, carefully analyse the provided information and prepare a comprehensive technical report with clear, evidence-based recommendations on whether to adopt compound T as a sucrose replacement in the new low-calorie beverage formulation.

Expected Response

Technical Report: Evaluation of Synthetic Sweetener T as a Sucrose Replacement
To: Production Manager, Kireka Beverage Manufacturing Company
From: Senior Chemistry Intern
Subject: Analysis and Recommendation on Adoption of Compound T in Low-Calorie Beverage Formulation
Date: June 2026

Introduction

The company is undergoing a major product reformulation to develop a new low-calorie soft drink. A key requirement is that the aqueous sweetener solution must not freeze at -0.33°C during processing. Compound T has been proposed as a replacement for sucrose ($\text{C}_{12}\text{H}_{22}\text{O}_{11}$) due to claims of greater stability. This report determines the molecular formula of T, compares its thermodynamic stability with sucrose, evaluates the masses required for the desired freezing point depression, and provides evidence-based recommendations.

Determination of Molecular Formula of T

Combustion Analysis of 0.50 g of T:

- Moles of $\text{CO}_2 = \frac{0.533}{22.4} = 0.02379 \text{ mol}$; Moles of carbon atoms = 0.02379 mol
- Moles of $\text{H}_2\text{O} = \frac{0.275}{18} = \mathbf{0.01528} \text{ mol}$; Amount of hydrogen atoms = $0.01528 \times 2 = 0.03056 \text{ mol}$.
- Moles of $\text{N}_2 = \frac{0.0381}{22.4} = \mathbf{0.00170} \text{ mol}$; Amount of Nitrogen atoms = $0.00170 \times 2 = 0.00340 \text{ mol}$

Mass of C = $0.02379 \times 12 = 0.2855 \text{ g}$

Mass of H = $0.03056 \times 1 = 0.0306 \text{ g}$

Mass of N = $0.00340 \times 14 = 0.0476 \text{ g}$

Mass of O = $0.50 - (0.2855 + 0.0306 + 0.0476) = 0.1363 \text{ g}$; Moles of O = $\frac{0.1363}{16} = 0.00852 \text{ mol}$

Mole ratio (dividing by smallest, 0.00170):

C : 14. H : 18. N : 2 O : 5

Empirical formula of T is $\text{C}_{14}\text{H}_{18}\text{N}_2\text{O}_5$

Given that,

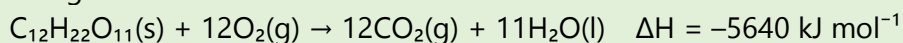
(Empirical formula mass)n = molecular formula mass;

$(12 \times 14 + 1 \times 18 + 14 \times 2 + 16 \times 5)n = 294.31$. $294n = 294.31$, $n = 1$.

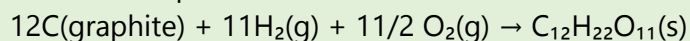
Molecular formula of T is $(\text{C}_{14}\text{H}_{18}\text{N}_2\text{O}_5)_1 = \mathbf{\text{C}_{14}\text{H}_{18}\text{N}_2\text{O}_5}$

Standard Enthalpy of Formation of Sucrose and Stability Comparison

Using Hess's Law for sucrose:



Formation equation:



$$\Delta\text{H}_f(\text{sucrose}) = [12 \times (-393.5) + 11 \times (-285.8)] - (-5640)$$

$$= [-4722 + -3143.8] + 5640$$

$$= -7865.8 + 5640 = -2225.8 \text{ kJ mol}^{-1}$$

Comparison:

ΔH_f of T = $-1273 \text{ kJ mol}^{-1}$ (much less negative than sucrose).

Sucrose is thermodynamically more stable.

Freezing point depression calculations

Required: $\Delta\text{T} = 0.33^\circ\text{C}$ (so freezing point = -0.33°C)

$$\Delta\text{T} = K_f \times m$$

Where m is the molality

$$\text{Molality required} = \frac{0.33}{1.86} = 0.1774 \text{ mol kg}^{-1}$$

For 1 litre or 1 kg of water:

Mass of Sucrose ($12 \times 12 + 1 \times 22 + 16 \times 11 = 342 \text{ g mol}^{-1}$):

$$0.1774 \times 342 = 60.7 \text{ g}$$

Mass of T ($M = 294.31 \text{ g mol}^{-1}$):

$$0.1774 \times 294.31 = 52.2 \text{ g}$$

More sucrose will be required to make a solution that does not freeze up to -0.33°C .

Recommendations

- A Significantly lower mass is required (52.2 g vs 60.7 g per litre) to achieve the same freezing point depression. Since the price per kilogram is the same, this results in lower material costs. So for cost reduction, adopt T.
- Sucrose has greater thermodynamic stability, for longer product shelf lives, maintain sucrose.

Item 2

A water treatment and sanitation company in Jinja is trying to formulate a new, more effective and safer disinfectant for municipal water supplies and hospital cleaning products. They are considering using different halogens or their compounds (chlorine, bromine, or iodine-based) as the active ingredient. They are hoping to use : aqueous solutions of the halogens, alkali based solutions and aqueous solutions of the halogen hydrides to be directly prepared by direct synthesis on site. However, recent trials have shown significant differences in reactivity, product effectiveness, stability under heat or sunlight, cost, and safety, leading to inconsistent product performance and growing concerns from environmental regulators about the ecological impact of halogen discharges into the Nile River.

The research team has provided the following data for the halogens fluorine, chlorine, bromine, and iodine to help resolve the crisis:

Halogen	Atomic Radius (pm)	Electronegativity (Pauling)	Cost per kilogram (UgX)
Fluorine	72	4.0	75000
Chlorine	99	3.0	25500
Bromine	114	2.8	124500
Iodine	133	2.5	250000

Task:

As an inorganic chemist in training hired by the company, carefully analyse the provided information and prepare a comprehensive and concise technical report with clear, evidence-based recommendations on the most suitable halogen-based disinfectant to adopt for large-scale production and use.

Expected Response

Selection of the most suitable halogen-based disinfectant

To: Management, Jinja Water Treatment and Sanitation Company

From: Inorganic Chemist in Training

Subject: Evidence-based recommendation for halogen disinfectant for municipal water and hospital Use

Date: June 2026

Introduction

The company seeks an effective, stable, safe, and cost-efficient halogen-based disinfectant for water treatment and hospital cleaning. This report analyses periodic trends of the halogens and their chemical behaviour to recommend the most suitable option while addressing safety, cost and environmental concerns.

Trends in reactivity of the halogens

Halogens react as electron accepting (oxidising agents). This is proportional to electronegativity – a measure of the atom of an element to draw bond electrons towards itself in a covalent bond situation. Electronegativity reduces with increase in atomic radii.

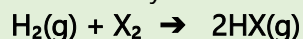
From the data:

Atomic radius increases down the group: F (72 pm) < Cl (99 pm) < Br (114 pm) < I (133 pm) because due to the successive addition of a full shell of electrons down the group, the shielding effect increases to outweigh the increase in the nuclear charge, so the effective nuclear charge on the outermost electrons or incoming electron reduces, leading to decreasing oxidising power and reactivity down the group ($F_2 > Cl_2 > Br_2 > I_2$).

For this reason the electronegativity decreases: F (4.0) > Cl (3.0) > Br (2.8) > I (2.5).

Reactivity trend illustrated by reactions with hydrogen and water

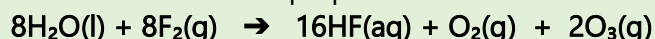
Fluorine reacts explosively with hydrogen even in the dark. Chlorine reacts vigorously in diffused sunlight, bromine requires heat; while iodine reacts slowly at a high temperature and reversibly even in the presence of a catalyst:



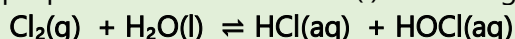
The H–X bond strength also decreases (HF strongest, HI weakest), because atomic size increase; bond lengths increase and electronegativities decrease from HF to HI, affecting the stability of the halogen hydrides we intend to produce on site.

Reaction with Water:

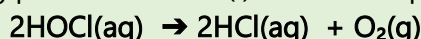
Fluorine reacts violently with water, producing HF and ozonised oxygen gas — a highly dangerous reaction unsuitable for on-site preparation.



Chlorine and bromine disproportionate to form halic(I) and halogen acids



The halic(I) acid is the active ingredient in a bleach, when the solution is exposed to sunlight, it loses its bleaching power. The halic(I) acid decomposes to halogen acid.

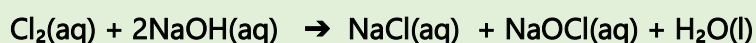


This affects the product performance.

Iodine dissolves very sparingly in water without reaction.

Reaction with Alkalis:

Chlorine and bromine react with cold dilute alkali to form the corresponding halate(I) and halide



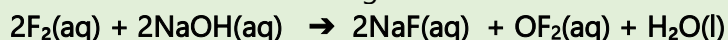
which are useful for disinfection.

When exposed to high temperatures, the halate(I) salts disproportionate to the halide and halate(V)



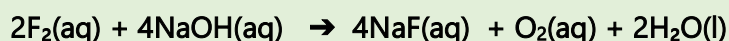
Iodine reacts forming the corresponding iodide and iodate(V) in solution

Fluorine's extreme reactivity leads to the formation of oxygen difluoride, the fluoride and water. The solution formed has little bleaching or disinfectant action.

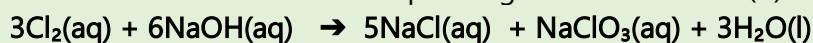


This makes it impractical and hazardous for alkali-based solutions.

With warm concentrated alkalis fluorine forms the fluoride and oxygen gas in a violent reaction



Chlorine, bromine and iodine form the corresponding halide and halate(V)



Evaluation and recommendation

I recommend chlorine-based disinfectants (primarily sodium chlorate(I) solution) for large-scale adoption because

- Chlorine has high oxidising power, making it highly effective for municipal water disinfection and hospital cleaning.
- At 25,500 UgX per kg, chlorine is the most affordable option compared to bromine (124,500 UgX) and iodine (250,000 UgX).
- While sensitive to sunlight, chlorate(I) solutions can be stabilised with proper storage. It is suitable for on-site preparation of both aqueous and alkali-based solutions.
- It is manageable with standard safety protocols, unlike the dangerously reactive fluorine.

- Bromine offers better stability but is significantly more expensive. Iodine is safer but too costly and less effective for large-scale water treatment. Fluorine is entirely unsuitable due to its extreme reactivity and safety risks.

Store solutions in opaque containers away from sunlight to prevent decomposition.

Environmental and health mitigation measures:

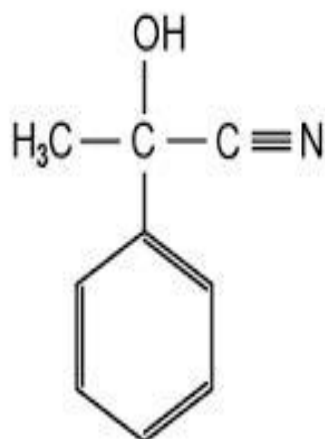
- Implement precise dosing systems to minimise excess chlorine.
- Treat any waste for dechlorination before any discharge into the Nile River.
- Workers should wear personal protective gear at all times while at work.

Item 3

A polymer manufacturing company in Masaka Industrial Park is facing a serious environmental and economic challenge. During the production of polystyrene, significant quantities of three organic by-products labelled U, V and W are generated and currently discharged as hazardous waste. This results in high disposal costs and serious pollution of nearby water bodies. The company's sustainability team wants to recover these by-products, understand their differing physical properties, and hence design ways to reformulate them into valuable chemicals to reduce environmental harm and generate additional income. The laboratory has isolated the three compounds and provided the following information:

- U: An aromatic hydrocarbon with molecular mass 104.
- V: An aromatic secondary alcohol with molecular mass 122.
- W: Aliphatic aldehyde, with benzene ring, molecular mass 120.

They think, but are unsure that the most promising pathway is to convert U and W into V and hence use V to synthesis 2-hydroxy-2-phenylpropanenitrile, a valuable intermediate for pharmaceutical synthesis. Its structural formula is below



Their uncertainty comes from lack of a clear understanding of how some of these reactions such as that leading to the formation of V from U.

Task:

As a training organic chemist advising the company, carefully analyse the information provided and prepare a comprehensive technical report with clear recommendations on how to recover and transform these by-products into valuable products to resolve the current environmental and economic crisis.

Expected Response

Recovery and reformulation of Polystyrene by-products U, V and W

To: Sustainability and production manager, Masaka industrial park polymer company

From: Training Organic Chemist

Subject: Recommended Pathways for recovery and conversion of by-products U, V and W into valuable intermediates

Date: June 2026

Introduction

The company generates significant quantities of organic by-products U, V and W during polystyrene production. These are currently discharged as hazardous waste, resulting in high disposal costs and pollution of nearby water bodies. This report identifies the compounds, explains their physical property differences, outlines key reaction mechanisms, and proposes an integrated recovery and reformulation strategy to convert them into 2-hydroxy-2-phenylpropanenitrile, a valuable pharmaceutical intermediate. The goal is to turn waste into revenue while addressing the environmental crisis.

Identification of compounds U, V and W

- U: Aromatic hydrocarbon, molecular mass 104, Phenylethene, $C_6H_5CH=CH_2$.
- V: Aromatic secondary alcohol, molecular mass 122, 1-Phenylethanol $C_6H_5CH(OH)CH_3$
- W: Aliphatic aldehyde, with benzene molecular mass 120, Phenylethanal $C_6H_5CH_2CHO$

Differences in physical properties of U, V and W

The physical properties differ due to differences in functional groups and intermolecular forces:

- U: is a non-polar molecule with only weak van der Waals forces that are easily overcome at low temperatures. It has a relatively low boiling point and is insoluble in water because it can not associate with water molecules that form intermolecular hydrogen bonds.
- V (1-Phenylethanol): Contains an –OH group capable of intermolecular hydrogen bonding. These bonds are much stronger than the weak van der waals forces This results in a significantly higher boiling point than U and moderate solubility in water with which it forms intermolecular hydrogen bonds.
- W (Phenylethanal): Contains a polar carbonyl group, the molecules associate through dipole – dipole attractions but cannot form strong intermolecular hydrogen bonds like V. It therefore has an intermediate boiling point and limited water solubility.

These differences are critical for designing separation like fractional distillation, steam distillation or solvent extraction; storage, and conversion processes.

Mechanism for formation of V from U

- Synthesis route from V to 2-Hydroxy-2-Phenylpropanenitrile
- Mechanism of cyanohydrin formation (Nucleophilic Addition):

Recommendations

- Prioritise recovery of U as the main feedstock and convert it to V via acid-catalysed hydration — this is the most direct and economically viable route.
- Recover W separately for sale for other purposes
- Implement on-site conversion of V to 2-hydroxy-2-phenylpropanenitrile to maximise value addition.
- Treat any waste before discharge into the local environment.