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Short Communication

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Reaction Mechanism of a New Variant of "Selective Reduction" Using Sodium Borohydride (NaBH_4) and Iodine (I_2)

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Abstract

Background: Reduction is one of the major chemical processes that takes place in life and laboratory as observed in photosynthesis (carbohydrates) and addition of hydrogen atoms to unsaturated compounds (alkenes, alkynes and carbonyls) respectively. **Objectives:** A reaction mechanism is proposed for a new variant of "selective" reduction using sodium borohydride (NaBH_4) and iodine (I_2). **Methodology:** Three compounds namely; gallic acid, vanillin and caffeic acid were separately reduced by sodium borohydride in iodine and the obtained products identified. **Results:** The identities of the reduced products had been revealed to be 3,4,5-trihydroxycyclohexyl methanol, o-methoxy-p-methyl cyclohexan-1-ol and 1-(3, 4-dihydroxy phenyl)-2-propen-3-ol (3, 4-benzenediol-2-propen-3-ol respectively in previously documented studies. Expectedly, the first two start-up compounds had their carbonyl ($-\text{C}=\text{O}$) groups reduced. In addition the aromatic endocyclic double bonds ($-\text{Ar}-\text{C}=\text{C}$) were similarly reduced which introduced a new twist (variant) to this particular reduction hence the essence of the proposed reaction mechanism. However, the third compound had only its $-\text{C}=\text{O}$ reduced while the double bonds (endocyclic and exocyclic) were left unreduced. **Conclusion:** The reaction mechanism for this variant of reduction shows that the associated electromeric and hyper-conjugation effects are resonance-stabilized in the transfer of electrons and or bonds over the carbon atom positions in the gallic acid which also serves as a reference for vanillin. This reaction mechanism is given trivial appellation-Olawale reduction mechanism.

Keywords: Reduction, NaBH_4 /iodine (I_2), Resonance, Electromeric, Hyper-conjugation

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1. Introduction

Chemistry is a scientific study or discipline of the properties and behaviour of substances (their compositions, structures, properties and changes that take place in reactions with other substances). Furthermore, it provides

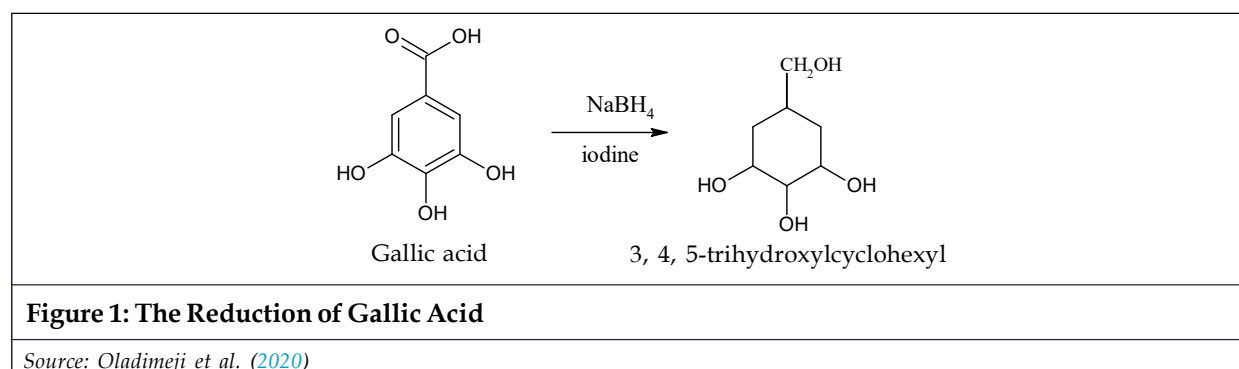
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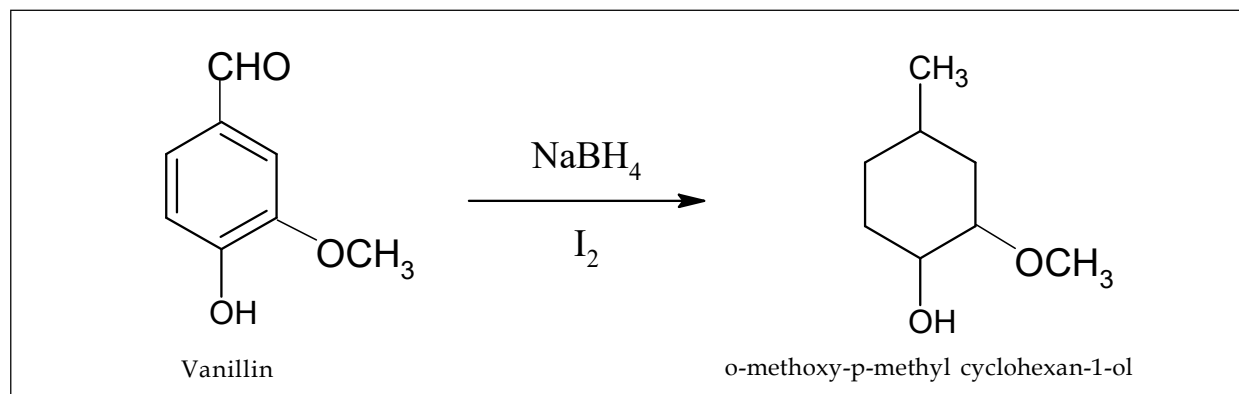
foundation for understanding between basic and applied disciplines such as in plant growth (botany), environmental pollution (ecology), medications (pharmacology), DNA evidence collection at crime scene (forensic science) amongst many others) (Brown *et al.*, 2018). Reduction is a huge class of chemical reactions in chemistry. This chemical process can be highlighted in as many as eight ways. It involves gain of electrons by a chemical entity or the addition of hydrogen atoms to an unsaturated compound. Furthermore, it is defined as the addition of electropositive atom(s) or addition of electron rich entities (nucleophiles) to electron deficient centres (electrophiles). Alternatively, it can be observed as the removal of oxygen or excision of electronegative moieties from substances (substrates) or removal of electrophiles from reacting substance or mixture. In addition it is taken as a decrease in oxidation state of a substance. It cuts across metallurgy, electroanalysis, metal-thermal processing (iron, chromium and molybdenum), reactions of organometallics, photosynthesis, carbohydrates (production of furfurals from pentosans) and reactions involving amines (pharmaceuticals, resins and fibres). There are a number of well known reduction reactions which include but not limited to the following: Catalytic addition of hydrogen atoms in the presence of metals such as nickel (Ni), platinum (Pt) or palladium (Pd) to alkenes and alkynes, reduction of alkynes to trans-alkenes using sodium (Na) or lithium (Li) in liquid ammonia, reduction of acyl chlorides with Pd-Barium sulphate (Rosenmund Reduction), reduction of carbonyls with Mg/HCl or Zn/HCl (Clemmensen Reduction), reduction of aldehydes, ketones, carboxylic acids, esters and acid halides to primary alcohols using lithium aluminium hydride (LiAlH₄)/ether and 'selective' reduction of carboxylic acids to alcohols using sodium borohydride (NaBH₄) and iodine (I₂) (Bhaskar *et al.*, 1991) amongst many others. Bhaskar *et al.* (1991) reduced a series of carboxylic and di-carboxylic acids (both aliphatic and aryl) to their corresponding mono or diol alcohols with only the -C=O being reduced to -CH₂. Similarly, this worker and fellow co-workers attempted to reduce gallic acid and vanillin (two aryl organic compounds with a carbonyl group attached to the phenyl ring) and caffeic acid with the -C=O group far from the aryl component in different studies. The results obtained were different from that of Bhaskar *et al.* (1991) in respect of gallic acid and vanillin resulting in derivatives that had their -C=O and the three endocyclic double bonds (-Ar-C=C) both reduced (Oladimeji *et al.*, 2020; 2022). However, the reduction of caffeic acid followed after that obtained in Bhaskar *et al.* (1991) as reported in Oladimeji *et al.* (2024). Hence, this short communication proposes a probable mechanism of reaction for this variant of 'selective' reduction with NaBH₄/I₂ with a aim of understanding the essence of the departure from (Bhaskar *et al.*, 1991) and also adding to existing literature.

2. Reduction Method (Bhaskar *et al.*, 1991)

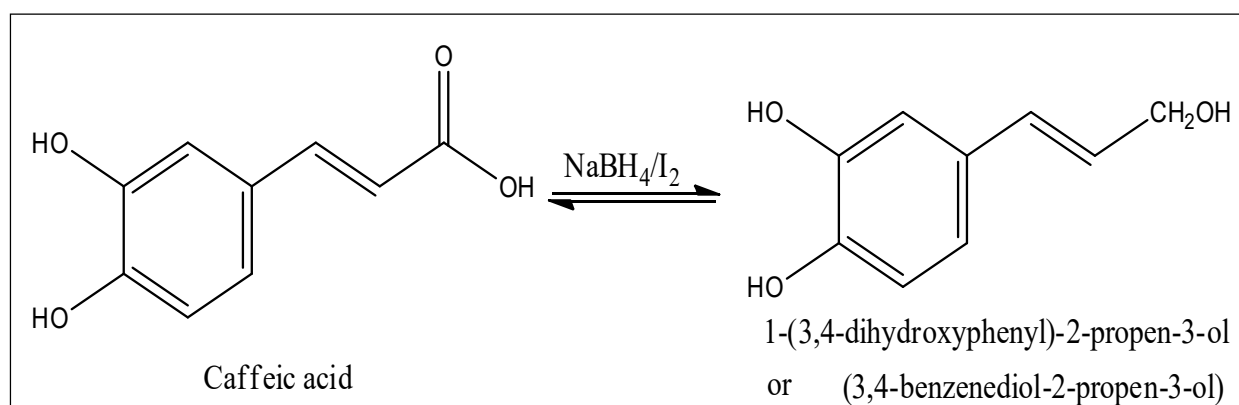
Separate solutions of gallic acid, vanillin and caffeic acid (1.80 g) in diethyl ether were slowly added to different suspensions of sodium borohydride (0.60 g) in diethyl ether (220 mL) at room temperature and left for fifteen (15) minutes. Each mixture was then stirred until evolution of gas ceased. Iodine (0.65 g) and diethyl ether (25 mL) was added to each reaction mixture slowly at a temperature of 0 °C (in ice) with further evolution of hydrogen gas. The contents were further stirred for an hour and half. Dilute hydrochloric acid (8 mL) was added carefully to the each mixture and extraction was done with diethyl ether. The combined ethereal extracts were washed with 3M sodium hydroxide (37 mL), brine and dried over silica gel. Evaporation of the organic layer gave the respective reduced product.

3. Results



**Figure 2: The Reduction of Vanillin**

Source: Oladimeji et al. (2022)

**Figure 3: The Reduction of Caffeic Acid**

Source: Oladimeji et al. (2024)

4. Spectral Analyses

Gallic acid: $\text{C}_7\text{H}_6\text{O}_5$; mol. wt. (170 g/mol); white crystalline solid; m.pt. (258-260 °C); $[\text{n}]_{\text{D}}^{20}$ (1.704); $[\alpha]_{\text{D}}^{20}$ (+38°); $[\text{d}]$ (1.69 g/cm³); FTIR (cm⁻¹): 1615 (-Ar-C=C), 1705 (-C=O), 2854 (-CH stretching), 2922 (-CH stretching), 3281 (-OH) and 3361 (-OH).

3, 4, 5-trihydroxycyclohexyl methanol (reduced derivative of gallic acid): $\text{C}_7\text{H}_{14}\text{O}_4$; mol. wt. (162 g/mol); colourless liquid; $[\text{n}]_{\text{D}}^{20}$ (1.6111); $[\alpha]_{\text{D}}^{20}$ (+30°); $[\text{d}]$ (1.30 g/cm³); FTIR (cm⁻¹): 2922 (-CH stretching) and 3437 (-OH).

Vanillin: $\text{C}_8\text{H}_8\text{O}_3$; mol. wt. (152.15 g/mol); white crystalline solid; m.pt. (80-82 °C); $[\text{n}]_{\text{D}}^{20}$ (1.5770); $[\alpha]_{\text{D}}^{20}$ (0°); λ_{max} (246 nm); R_{f} (0.66); FTIR (cm⁻¹): 1146 (-C-O-C), 1575 (-Ar-C=C), 1634 (-C=O), 2847 (-CH stretching) and 3179 (-Ar-OH).

o-methoxy-p-methyl cyclohexan-1-ol (reduced derivative of vanillin): $\text{C}_8\text{H}_{16}\text{O}_2$; mol. wt. (144.14 g/mol); colourless liquid; $[\text{n}]_{\text{D}}^{20}$ (1.5773); $[\alpha]_{\text{D}}^{20}$ (0°); λ_{max} (370 nm); R_{f} (0.89); FTIR (cm⁻¹): 1161 (C-O-C) and 3460 (-OH).

Caffeic acid: $\text{C}_9\text{H}_8\text{O}_4$; mol. wt. (180.16 g/mol); odourless brownish yellow crystalline solid; m.pt. (221-223 °C); $[\text{n}]_{\text{D}}^{20}$ (1.3934); $[\alpha]_{\text{D}}^{20}$ (+0.267°); λ_{max} (230 nm); R_{f} (0.58); FTIR (cm⁻¹): 1589 (-Ar-C=C), 1614 (acyclic -C=C), 1723 (-C=O), 2885 (-CH stretching) 3130 (alcoholic-OH) and 3479 (-Ar-OH).

1-(3, 4-dihydroxy phenyl)-2-propen-3-ol (3, 4-benzenediol-2-propen-3-ol) (reduced derivative of caffeic acid): $\text{C}_9\text{H}_{10}\text{O}_3$; mol. wt. (166.04 g/mol); viscous yellow liquid; $[\text{n}]_{\text{D}}^{20}$ (1.5191); $[\alpha]_{\text{D}}^{20}$ (0°); λ_{max} (332 nm); R_{f} (0.88); FTIR (cm⁻¹): 1587 (-Ar-C=C), 1612 (acyclic -C=C), 2935 (-CH stretching) 3125 (alcoholic -OH) and 3429 (-Ar-OH).

5. Mechanism of Reaction

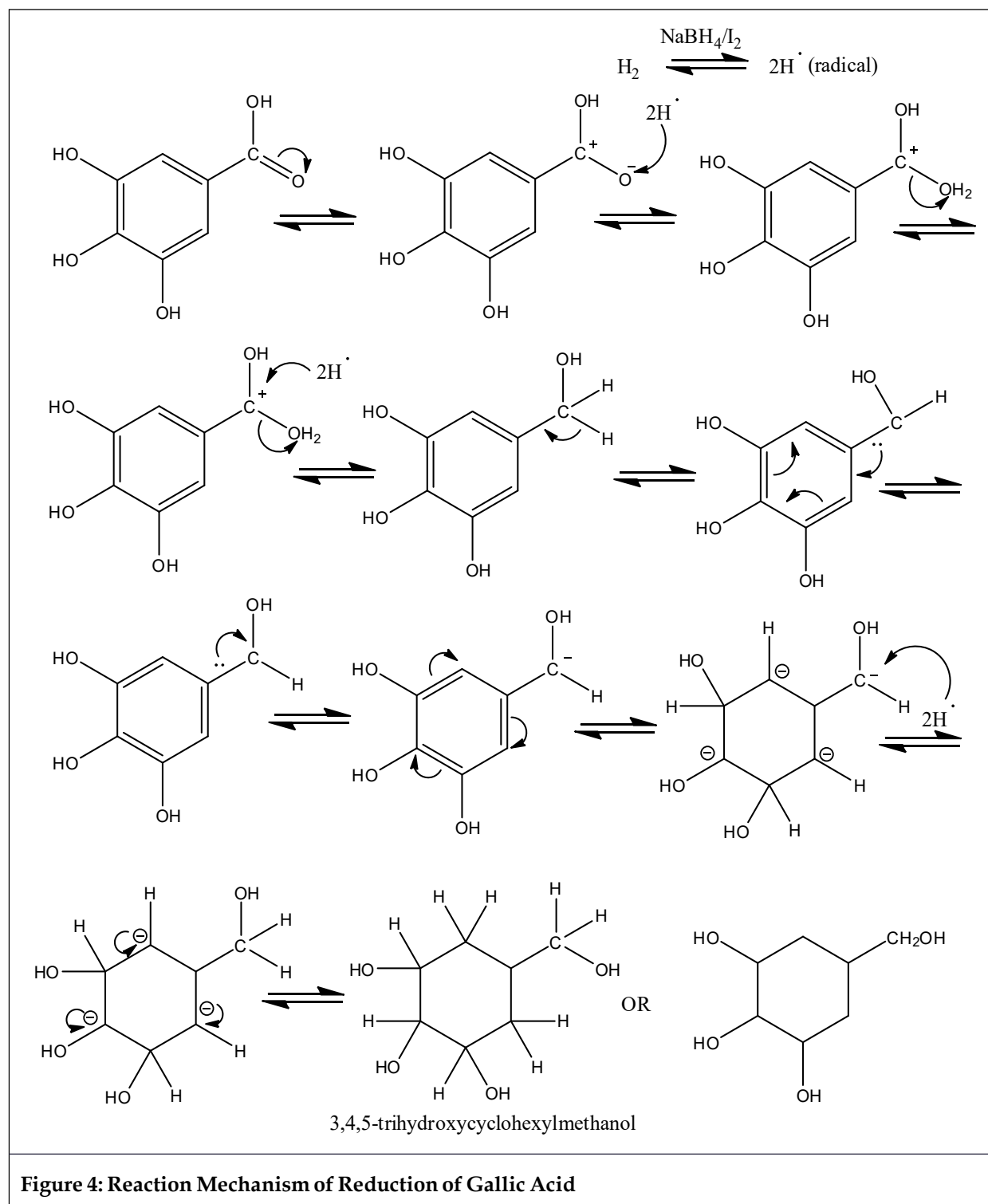


Figure 4: Reaction Mechanism of Reduction of Gallic Acid

6. Discussion

Considering the IR matrices of the gallic acid, vanillin, caffeic acid and their corresponding reduced derivatives as presented above, the following inferences can be made. The emboldened stretchings at 1615 cm^{-1} ($-\text{Ar}-\text{C}=\text{C}$) and 1705 cm^{-1} ($-\text{C}=\text{O}$) (Figure 1) in the gallic acid both disappeared in the reduced derivative (3, 4, 5-trihydroxycyclohexyl methanol) (Figure 1). Similarly, the aromatic double bonds and carbonyl peaks at 1575 and 1634 cm^{-1} as evident in vanillin both vanished in its reduced product (o-methoxy-p-methyl cyclohexan-1-ol) (Figure 2). However, the three endocyclic double bonds in the reduced derivative of caffeic acid (1-(3, 4-dihydroxy phenyl)-2-propen-3-ol (3, 4-benzenediol-2-propen-3-ol) (Figure 3) were not affected by the reduction

but only the -C=O absorption due to reduction. The proposed mechanism of reaction for the reduction of gallic acid or vanillin occurs in many stages starting with the initiation phase of conversion of hydrogen atoms to hydrogen radicals. Using gallic acid as the reference compound, the reaction mechanism begins with a chain initiation step where hydrogen atoms are converted into 2H radicals which ordinarily should act as electron rich entities but can in some instances behave chemically as electron deficient moieties such as in cellular metabolism) (Phaniendra *et al.*, 2015) as can be seen in this mechanism. The chemical processes of hyper-conjugation and carbonyl effects are stabilized by resonance as highlighted in the reaction mechanism.

Hence, electrons and bonds move from one carbon position to another in a series of hyper-conjugation and carbonyl processes as exhibited in the mechanistic scheme (Figure 4). Firstly the carbonyl on the aryl ring is successfully reduced. Furthermore, a convoluted series of electro/bond exchanges as seen in the latter phases leading to the unambiguous reduction of endocyclic double bonds in the termination stage.

7. Conclusion

This short communication reports a new reaction mechanism for the reduction of compounds such as gallic acid or vanillin in NaBH_4/I_2 . It is characterized by formation of the hydrogen radicals from hydrogen atoms in the initiation stage. Subsequent phases indicate the distributions of electrons/bonds by resonance stabilization of hyper-conjugation and carbonyl effects over the inherent carbon positions on the aryl ring. This mechanism is accorded the trivial description of Olawale-reduction mechanism.

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