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The Performance of Red Flares $Mg/Sr(NO_3)_2/PVC$ Compositions Modified with KIO_4 Additives

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Abstract— This study analyzes the enhancement of red signal flare efficacy for defense applications by formulating $Mg/Sr(NO_3)_2/PVC$-based pyrotechnics, utilizing various quantities of potassium periodate (KIO_4) as a secondary oxidizer. The addition of KIO_4 is significant as it provides extra oxygen, modifies combus6tion kinetics, raises flame temperature, and enhances the stimulating effect of red-emitting species—mechanisms that together may increase luminous output and stabilize the emitted spectrum band. Performance was assessed by measuring light intensity, dominant wavelength, burn rate, and color purity; spectral and image-based color analyses were performed using ImageJ. Results indicate that formulations containing up to 10% KIO_4 achieve a peak light intensity of 3,173.33 lux, a dominant wavelength of 638.16 nm, a burn rate of 2.01 g/s, and an estimated photon-energy efficiency of 3.54×10^{-19} J, with red emission reaching optimal purity at this composition. Compared to the baseline formulation without KIO_4, KIO_4-containing compositions showed markedly higher intensity and improved spectral stability, faster and more consistent burn behavior, and enhanced color purity—whereas the formulation without KIO_4 exhibited lower luminous output, broader or shifted spectral features, and reduced color stability. The novelty of this work lies in applying potassium periodate as a secondary oxidizer in the $Mg/Sr(NO_3)_2/PVC$ system—an approach that, to our knowledge, has been little explored—and demonstrating its dual benefit for optical performance and combustion behavior. The findings support the recommendation of the 10% KIO_4 formulation as the most effective balance of visual and combustion performance for red signal flares.

Keywords— *Burning rate; Light intensity; Red flare pyrotechnics; Potassium periodate; Wavelength.*

1. INTRODUCTION

The independence of the defense industry in Indonesia needs to be increased, as it still relies on imports for the supply of the main weapon system. Indonesia has launched seven priority programs to build an effective and efficient defense industry. Yet, dependence on imported components and raw materials persists, as domestic supporting industries remain unable to fully meet the requirements of primary defense systems. This reliance underscores the challenge of achieving self-reliance amid global supply chain vulnerabilities. [1]. The role of the Ministry of Defense in increasing the independence of the defense industry is to establish Law Number 16 concerning the Defense Industry in meeting the needs of Army's Defense Equipment and achieving Minimum Essential Force (MEF) Phase I. The target that Indonesia wants to achieve is to be independent in the procurement of Defense Equipment by 2029 [2].

One way to maximize the need for defense equipment is by developing domestic defense equipment, for example, in pyrotechnics. Pyrotechnic compositions are typically based on oxidizers and fuels to produce visual, thermal, sound or mechanical terminal effects, such as smoke, light, loud sounds, and colors [3]. Light pyrotechnics are one of the defense equipment that can be developed for a light source on a battlefield. Light pyrotechnics produce emissions in the form of light in the visible range (380 to 780 nm) [4]. Light of various colors uses metal compounds that produce spectral emissions with characteristic frequencies [5].

Light pyrotechnics appear in several colors across the spectrum, ranging from yellow, red, green, purple, to blue [6]. The resulting light pyrotechnic applications can be used as markers of emergencies, missions that have been stopped, and traffic accidents, as well as in the world of entertainment and the military. Previous research in making red flares generally used perchlorate because it produces chloride compounds that can increase color intensity [7]. However, perchlorate materials are toxic in that they can contaminate water

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and soil [8]. Strontium nitrate ($Sr(NO_3)_2$) is one of the potential compounds to replace the role of perchlorate as an oxidizer that produces a deep red flame (**Fig. 1**) [9,10].

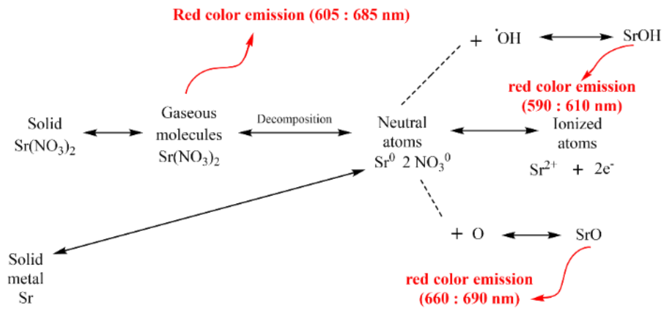

Fig. 1 Strontium nitrate reaction as a producer of emissions in red flares

The combustion of strontium nitrate ($Sr(NO_3)_2$) in red flares requires fuel. Magnesium (Mg) is one of the fuels that can oxidize and release a large amount of heat during the combustion process [11]. Binders are needed in such reactions as binders in the composition of flares, one of which can use polyvinyl chloride (PVC). Polyvinyl chloride (PVC) material is required to produce chlorine elements in small amounts as a color enhancer [12]. Potassium periodate (KIO4) is added to the composition in place of perchlorate to improve the performance of red flares [13].

Previous research has shown that potassium periodate (KIO_4) in the composition of $Mg/Sr(NO_3)_2$/PVC-based red flares can increase light intensity, combustion rate, and emission spectrum [14]. However, there is no reference to the optimal amount of potassium periodate (KIO4) added so that performance can be improved. In this study, the author will deeply examine the effect of KIO_4 addition on the $Mg/Sr(NO_3)_2$/PVC performance and discuss the best component for red flares' further development.

2. EXPERIMENTAL SECTION

2.1. Materials & Instrumentations

All chemicals (strontium nitrate ($Sr(NO_3)_2$, 99%, Alpha Chemika), magnesium (Mg, 99%, ROFA Laboratory Center), polyvinyl chloride resin (PVC, Kimia Market), potassium periodate (KIO_4, 99%, Maxlab)) were pro-analysis. Other materials are small diameter cardboard (canist), wooden board, wood glue, and diffraction lattice.

The tools needed in this research are, FLUKE Light Meter FLK-941 ESP, Theremino Spectrometer, blasting machine, laptop (RAM min. 2GB, Windows 7/8/10/11), oven, analytical balance, pan, mortar, spatula, mini container, mesh sieve (size 45, 70, 80 and 100), stopwatch, webcam resolution (min. 640x480 pixels).

2.2. Formulation of Strontium Nitrate–Magnesium–PVC with KIO_4 Additive

The preparation of pyrotechnic compositions began with the drying of strontium nitrate at 80 °C for 4 h, followed by sieving to obtain a particle size of 100–180 μm, while magnesium was dried at 50 °C for 4 h and sieved to 125–210 μm. Potassium periodate and PVC resin were also dried at 50 °C for 4 hours and then sieved through a 100-mesh sieve (particle size: <0.153 mm). The variation composition of pyrotechnic material is shown in **Table 1.**

Table 1. Variations in the composition of red flare pyrotechnics

Oxidizer (g)	Fuel (g)	Binder (g)	Additive (g)	Additive (%)	Ref
5.400	3.100	1.5	0	0	[15]
5.270	3.030	1.5	0.2	2	[15]
5.145	2.955	1.5	0.4	4	[15]
5.018	2.882	1.5	0.6	6	[15]
4.890	2.810	1.5	0.8	8	[15]
4.760	2.740	1.5	1.0	10	[16]
4.630	2.670	1.5	1.2	12	[17]
4.510	2.590	1.5	1.4	14	[17]

Each component was then weighed according to its composition, homogenized by manual grinding with a mortar for 3 minutes, dried again at 60 °C for 2 hours, and sieved through a 375 μm sieve. To ensure minimum moisture content, the mixture was further granulated and heated at 60 °C for 4 h. The prepared pyrotechnic mixture was subsequently loaded into small cardboard tubes, compacted using a manual hand press, and fitted with a squib placed above a layer of black powder to initiate the red flare upon electrical ignition

2.3. Measurement of Pyrotechnic Performance

The pyrotechnic samples were evaluated using a performance testing apparatus consisting of four main components: a gas chamber, a burn rate tester, an emission spectrometer, and a luxmeter. The emission spectrometer was employed to record the spectral wavelengths of the pyrotechnic emissions, while the luxmeter measured their light intensity. The burn rate tester determined the combustion duration of the samples, and the gas chamber functioned to prevent interference with the measurements. The experimental setup is illustrated in **Fig. 2.** The samples were initiated by a 12 V [18].

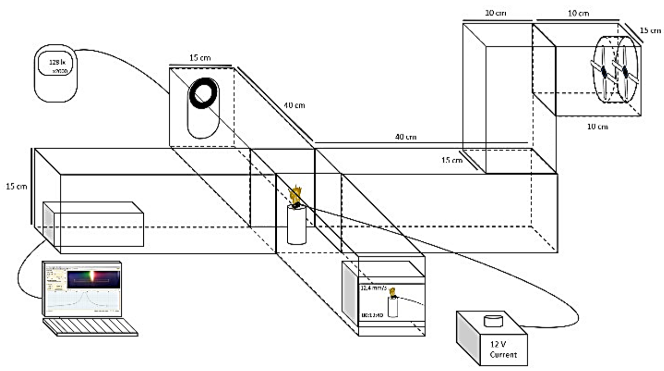

Fig. 2 Three dimensional design for pyrotechnic performance measurement device

3. RESULT AND DISCUSSION

Observation of the physical characteristics of Mg/$Sr(NO_3)_2$/PVC-based red flare pyrotechnics with the addition of potassium periodate (KIO_4) additives showed that mixing resulted in a homogeneous powder composition (**Fig. 3**). The pyrotechnic material before the stirring process has an uneven mixture, namely, there are still clumps of white powder from strontium nitrate ($Sr(NO_3)_2$) and black color from magnesium (Mg). Then, after manual mixing using a mixture mortar, the pyrotechnic material becomes more homogeneous with the color mixed to light gray.

Pyrotechnic combustion produces a red flame that indicates a strong exothermic reaction. Magnesium acts as the main fuel that oxidizes and produces high heat. This exothermic reaction causesx the ambient temperature of combustion to increase drastically to above 3000 K [19]. The heat from combustion allows the decomposition of $Sr(NO_3)_2$, resulting in excited Sr atoms. The transition of the Sr electron from the 5p to 5s orbitals results in a red light emission with a wavelength of 606-631 nm. PVC serves as a binder and a chlorine donor that reacts with SrO to form $SrCl_2$, increasing the intensity of red emissions.

The incorporation of KIO_4 introduces periodate ions that decompose at elevated temperatures, releasing oxygen and thereby strengthening the oxidizing environment. This condition accelerates the combustion of magnesium, producing higher localized temperatures that enhance the excitation of strontium atoms. Furthermore, the stronger oxidizing potential suppresses incomplete combustion products, stabilizes the formation of $SrCl_2$ through reaction with chlorine released from PVC, and ultimately improves both the spectral purity and luminous efficiency of the red flame [20].

The total combustion reaction of red light pyrotechnic material is as follows the reaction equation (1).

$$5Mg(s) + Sr(NO_3)_2(s) + (C_2H_3Cl)_n(s) + KIO_4(s) \rightarrow SrCl_2(s) + 5MgO(s) + KI(s) + 2NO_2(g) + 2CO_2(g) + 3H_2O(g) + CH_2{=}CH + \text{Energy (Red Flame)} \quad (1)$$

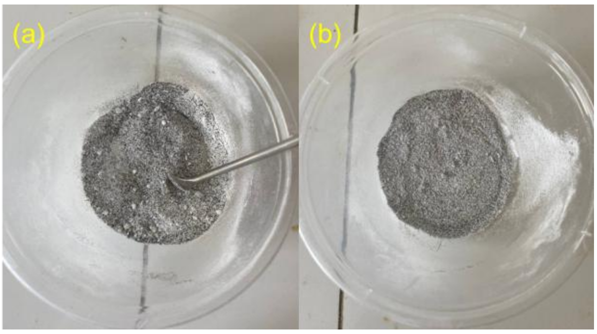

Fig. 3 (a) Pyrotechnic materials before stirring, and (b) Pyrotechnics after stirring

3.1. Pyrotechnic Light Intensity

Light intensity characteristic tests are crucial as pyrotechnics are often used at night for lighting and signaling applications [21]. The results of the light intensity test showed that the addition of potassium periodate (KIO_4) additives to red light pyrotechnics from a composition of 2% to 10% contributed to an increase in the intensity of the resulting light. The KIO_4 composition of 10% produces the highest light intensity of all variations, with an average value of 3173.33 lux (**Table 2** and **Fig. 4**).

This shows that a KIO_4 variation of 10% is the optimal composition for the tested red-light pyrotechnic formulation, as it produced the highest luminous output (3,173.33 lux) and the best spectral purity. Studies reporting that periodate salts (e.g., KIO_4) enhance oxidizing power and combustion performance, and that strontium/chloride species produce strong red flame emission, support this interpretation [12].

The addition of KIO_4 further accelerates this process through its thermal decomposition that produces potassium iodide (KI) and additional oxygen [22]. This additional oxygen accelerates the reaction rate of Mg and Sr, thereby increasing the excitation temperature of the Sr atoms responsible for red light emissions. The results of the study [23] show that increased excitation temperature of Sr can result in higher intensity light emission. According to research, periodate compounds have the potential to improve combustion efficiency and light output [24].

The increase in light intensity of up to 10% KIO_4 is due to the greater availability of oxygen in the reaction system [25]. KIO_4, as a strong oxidizer, decomposes at high temperatures to produce O_2 that supports optimal Mg combustion. This extra oxygen accelerates the excitation of the Sr atoms, resulting in more intense red

Table 2. Effect of KIO_4 additives on light intensity

Variation KIO_4 (g)	Light intensity (Lux)			
	Rep. I	Rep. II	Rep. III	Mean
0	1149	1710	1130	1329.67
0.2	1470	1030	1657	1385.67
0.4	1110	1641	1012	1254.33
0.6	1830	1999	1124	1651.00
0.8	3200	3200	1373	2591.00
1.0	3160	3160	3200	3173.33
1.2	1271	3160	2320	2250.33
1.4	3000	3160	2590	2916.67

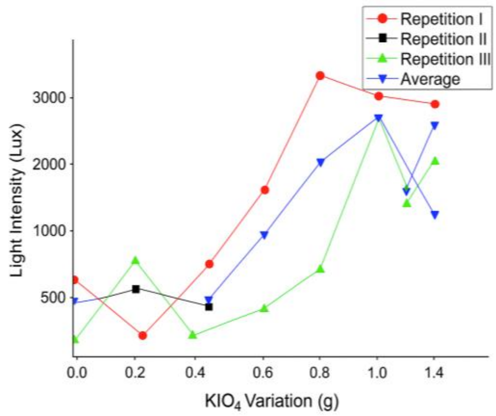

Fig. 4 Effect of KIO_4 variation on light intensity (Lux)

light emissions. The addition of KIO_4 above 10% causes a decrease in intensity due to an imbalance of oxidizer composition and over-fast or uncontrolled combustion.

3.2. Red Color Wavelength

Structural wavelength performance analysis can be performed using a simple emission spectrometer equipped with a monochromator to separate polychromatic light into monochromatic light. The results of analysis using an emission spectrometer showed that the addition of KIO_4 affected the dominant wavelength produced. The 10% KIO_4 composition results in a maximum wavelength value of 638.16 nm (**Table 3**), which is consistent with the characteristic red emission of strontium-based pyrotechnic systems typically observed in the 630–640 nm range [26]. In several previous studies, it has been mentioned that some additives, such as guanidium nitrate and potassium periodate (KIO_4), have the highest intensity levels in red light pyrotechnics [27].

The increase in wavelength from 531 nm (0% KIO_4 composition) to 638.16 nm (10% KIO_4 composition) indicates a color shift towards a stronger red (**Fig. 5**). This is attributed to the optimization of combustion temperature that favors the excitation of Sr. Ion Sr^{2+} with the electron configuration [Kr] $5s^0$ undergoes a dominant electron transition between the 5p orbitals → 5s and 6s → 5p, resulting in emissions in the range of 606-676 nm [28]. Excess KIO_4 (12% and 14%) causes thermal instability that interferes with the dominance of strontium emissions.

Table 3. Dominant wavelengths of pyrotechnic emissions

Variation KIO_4 (g)	Wavelength (nm)			
	Rep. I	Rep. II	Rep. III	Mean
0	536.0	512.0	545.0	531.00
0.2	561.0	544.0	510.0	538.30
0.4	547.9	528.9	559.5	545.43
0.6	681.4	555.6	566.9	601.30
0.8	587.0	592.4	699.2	626.20
1.0	718.5	610.1	585.9	638.16
1.2	561.0	550.5	634.3	581.93
1.4	615.4	617.0	618.0	616.76

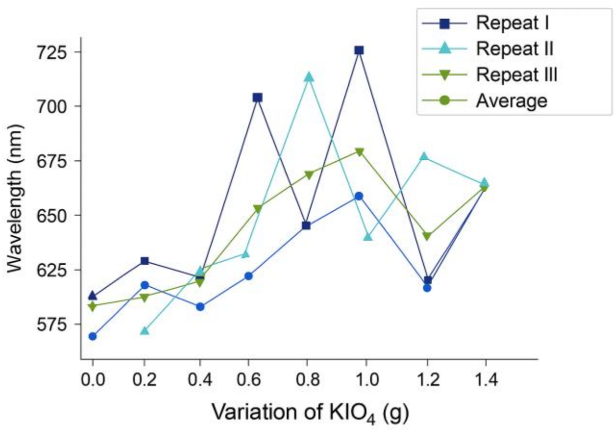

Fig. 5 Graph of the effect of KIO_4 additives on wavelength

3.3. Pyrotechnic Combustion Rate

The rate of combustion in pyrotechnics indicates how long a pyrotechnic flame can last over a period of time [29]. Combustion rate testing showed a complex pattern with a decrease from 0% to 8% KIO_4. At the addition of KIO_4 concentration, below 10% the combustion rate tends to decrease (**Table 4** and **Fig. 6**). This can be caused by additives that reduce the proportion of primary fuels (Mg and PVC) in the mixture, resulting in a less optimal ratio of fuel to oxidizer and reduced combustion efficiency.

Compositions above 10% then increase at higher concentrations. This increase may be due to higher oxidation efficiency, where the decomposition of KIO_4 produces sufficient amounts of oxygen to increase combustion efficiency. In addition, the interaction between KIO_4 and $Sr(NO_3)_2$ at higher levels can create a more oxidizer-rich reaction environment, accelerate exothermic reactions, and increase the rate of combustion.

Table 4. Effect of KIO_4 on combustion rate

Variation KIO_4 (g)	Combustion Rate (g/s)			
	Rep. I	Rep. II	Rep. III	Mean
0	2.07	2.18	1.86	2.04
0.2	1.79	2.21	2.07	2.02
0.4	1.82	1.79	1.96	1.85
0.6	1.73	1.66	1.71	1.70
0.8	1.70	1.81	1.68	1.73
1.0	2.35	1.90	1.77	2.01
1.2	2.13	2.25	1.90	2.09
1.4	2.12	2.55	2.09	2.25

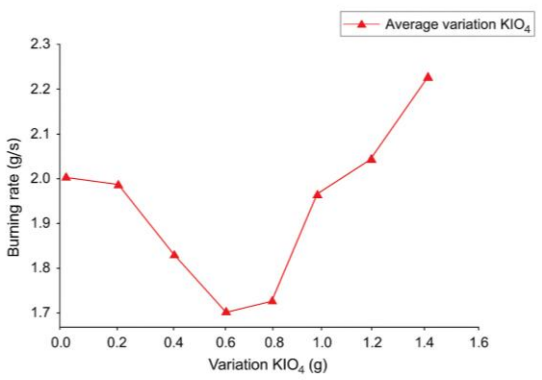

Fig. 6 Average variation in KIO_4 composition to combustion rate

3.4. RGB and Pyrotechnic Spectrum Analysis

RGB (Red, Green, Blue) analysis is a colour modeling used to describe and reproduce colors by mixing three basic colors. RGB can be used to analyze the spectral composition of an object based on reflections at different wavelengths. RGB analysis using the ImageJ application with the Colour Inspector 3D method showed that an increase in KIO_4 concentration of up to 10% resulted in a gradual increase in red intensity with a decrease in white components (**Fig. 7**).

The composition of 10% KIO_4 shows optimal red

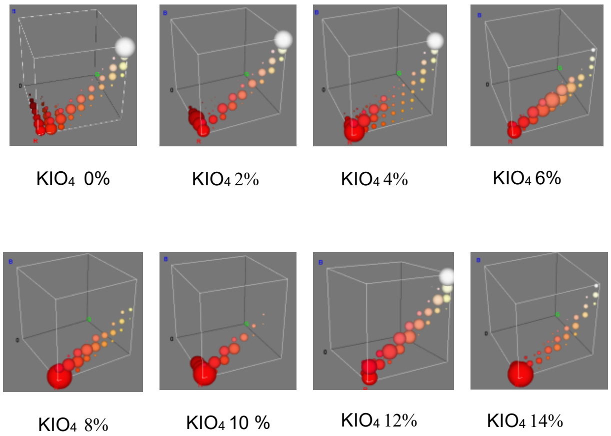

Fig. 7 Pyrotechnic sample RGB analysis results

dominance compared to other variations. After exceeding 10%, there is a decrease in the intensity of the red color, which is characterized by the appearance of more orange and white colors, indicating an imbalance in the combustion reaction. This indicates that KIO_4 has a significant role in increasing the emission of the dominant red color, which is thought to be due to the increased combustion reaction efficiency and excitation of strontium ions (Sr^{2+}), resulting in a red spectrum of higher intensity [30].

3.5. Optimum Composition and Standard

Based on a comprehensive evaluation of light intensity, wavelength, and combustion rate, the composition of 10% KIO_4 was established as the optimal formulation. In this composition, the light intensity reaches a maximum value of 3173.33 lux, indicating a very high level of flame brightness. The emission wavelength also showed the best results, which was 638.16 nm, which is in the deep red color range and indicates high color spectral purity. Comparison with military standards shows that this composition meets the requirements of STANAG 4487 and Mk 124 Mod 0 MSIS.

Standardization Agreement (STANAG) 4487 is a NATO standard that regulates technical specifications for pyrotechnic signals, including red flares. These standards set minimum performance parameters to ensure consistency among NATO member states. The second standard, the Mk 124 Mod 0, is a red color smoke and illumination signal developed by the United States military and widely used in rescue operations and emergencies. The Mk 124 Mod 0 is designed to provide high visibility in day and night conditions with a relatively longer duration compared to some other standards.

4. CONCLUSION

This study shows that the addition of potassium periodate (KIO_4) additives in pyrotechnic compositions based on $Mg/Sr(NO_3)_2/PVC$ is able to improve system performance, especially at a concentration of 10% which provides the most optimal light intensity, wavelength, and combustion rate. These findings confirm the role of KIO_4 as an effective supplemental oxygen source in improving the combustion efficiency and quality of pyrotechnic light. Thus, the use of KIO_4 has the potential to be applied in modern pyrotechnic formulations that require high intensity, stability, and better visual display.

Further research development is recommended to examine the physical parameters of the materials such as surface area, density, porosity, particle size distribution, and moisture content to deepen understanding of factors that influence pyrotechnic system performance; to perform thermal characterization using DSC and TGA to assess thermal stability and decomposition mechanisms of the compositions; and to evaluate visual properties through CIE chromaticity analysis while investigating the environmental impact of combustion residues and developing safer, more efficient, and more sustainable KIO_4 based production methods.

5. AUTHOR’S DECLARATION

5.1. Supporting Information

There is no supporting information in this paper. The data supporting this research’s findings are available on request from the corresponding author (Gunaryo).

5.2. Acknowledgements

The authors gratefully acknowledge the financial assistance provided by the Department of Chemistry, Republic of Indonesia Defense University.

5.3. Conflict of Interest

There was no conflict of interest in this study.

5.4. Author Contributions

EP conducted the experiment. G, AM, and MW conceptualized the research. AB, SA, and SAW wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

5.5. AI Statement

ChatGPT was utilize to enhance the clarity, grammar, and overall readability of this manuscript. All technical content, data interpretation, and conclusion were solely developed and verified by the authors. The final version of the manuscript was thoroughly reviewed to ensure accuracy, coherence, and aligment with the study’s findings.

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