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Digital Crackers as a Sustainable Alternative: Designing a High-Decibel, Emission-Free Firework Simulation Using Node Mcu

Lalit Kumar[1], Aayush Shrivastava[2], Abhishek Sharma[3], Ritu Gupta[4]
[1] Department of CSE, MMEC, Maharishi Markandeshwar Deemed to be University, Mullana, Ambala, India
Email: lalit.cse@gmail.com
[2] Department of CSE, MMEC, Maharishi Markandeshwar Deemed to be University, Mullana, Ambala, India
Email: mr.aayushshrivastava@gmail.com
[3] Computer science and engineering department, Graphic Era Deemed to be University, Dehradun, India
Email: abhishek15491@gmail.com
[4] Department of ECE, Chandigarh University, Gharaun – Mohali, India
Email: erritugupta02@gmail.com

Abstract: Using digital crackers be a part of modern, digital India, a step closer towards sustainable and safe health-focused Diwali. This study investigates the use of digital crackers instead of fireworks, which cause a lot of air and noise pollution. Digital crackers utilise advanced technologies such as AR, VR, IoT-based devices, and LED-based simulators that not only ensure a safe, reusable, and eco-friendly experience but also provide a rich usage experience. Here, we propose a Node MCU-based prototype to mimic firework effects with visual as well as auditory effects without producing any emission of pollutants and low noise. Data was collected on the prototype energy efficiencies, noise impact, cost-effectiveness, and user perspective under a controlled environment. Findings showed digital crackers offer potential to be an eco-friendly alternative to the bursting of traditional firecrackers while garnering widespread user acceptance, suggesting these can be mainstreamed to shape future festive practices.

Keywords: Digital Crackers, Sustainable Celebrations, IoT, NodeMCU, Eco-Friendly Fireworks.

1. Introduction

Firecrackers have been an integral part of festivals, which are an occasion of cultural legacy and community celebration; a moment of brilliance of light, color, and sound to worship the gods. Although traditional firecrackers have been a common practice during celebrations, their usage is attracting growing concern as they contribute to air pollution, negative health impacts, and environmental degradation. Pyrotechnic material combustion produces unsafe air pollutants, such as fine particulate matter (PM2.5 and PM10), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and heavy metals. Such emissions lead to a rise in respiratory and cardiovascular diseases among vulnerable populations, especially children, the elderly, and people with chronic diseases. In addition, the explosions produced by firecrackers usually top 120 dB, which endangers hearing and terrifies pets and people who are neurodivergent.

With growing environmental awareness and stricter regulatory measures, this has led to the development of virtual alternatives, Digital crackers are a prospective alternative. Implemented using LED lights, piezo buzzers, augmented reality (AR), virtual reality (VR), and mobile applications, digital crackers seek to replicate the sensory charm of fireworks without the harmful emissions and noise pollution. They are safer, reusable, scalable, customizable, and inclusive for sensitive populations.

This paper discusses the potential sustainability of digital crackers and provides evidence of a working prototype based on NodeMCU (ESP8266) along with real-time performance evaluation. We hope to show that the usage of such technological innovations can preserve the cultural core of celebrations while massively shrinking their ecological footprint. Such use of digital crackers is in line with the world and the nation's targets for green celebrations and smart connected living.

2. Literature Review

The use of firecrackers around festivals has deleterious environmental and health impacts, especially so in urban landscapes, has been well-established in recent years. Several studies have called for alternatives to traditional fireworks.

(Nasir and Brahmaiah 2015), through a more in-depth study of the Diwali episode at New Delhi, reported a significant increase in PM2.5. Levels 5 (Figure 1), which are known to be harmful to health due to the combustion of firecrackers. Using ground-based and satellite data, the final paper in the series illustrated how the use of firecrackers during Diwali severely exacerbates already unhealthy levels of pollution.

Similarly, (Thakur et al. 2024) studied the impact of air pollution [2.5] generated by the burning of firecrackers in Delhi on twenty-six days before and after Diwali and estimated that firecrackers add 40 $\mu g/m^3$ to PM2. 5 concentrations, worsening wintertime air quality concerns and public health risks.

(Singh and Srivastava 2020) study on technological adoption and digital transformation in SMEs during COVID-19 focuses on food manufacturers in Jember Regency (i.e., crackers). They were able to show that technology adoption, including the digital way, contributed significantly to maintaining productivity and navigating the changing market, information that will also fit digital crackers being a product of the digital transformation in festival tools.

(Manglani et al. 2022) reviewed difficulties of software versioning and the security of a software emulation system, which is similar to a Digital Rights Management system (DRM). The research investigated vulnerabilities in simulated software and mentioned the need for robustness in digital applications. This context is important for understanding the design, armoring, and deployment of digital firecracker simulation platforms.

Together, these studies provide corroboration for such a shift toward cleaner, smarter, and more secure alternatives to conventional practices. They offer empirical evidence and theoretical explanations for the production and utilization of digital crackers as an eco-friendly, health-oriented, and technologically sophisticated way of celebration.

2.1 Impact of Traditional Firecrackers

The use of firecrackers in festivals leads to an ominous increase in air Pollution levels; numerous studies work as aids to identify these concerning trends. Then, according to (Thakur et al. 2024), PM2. During Diwali, 5 levels in Delhi were increased by ~40 $\mu g/m^3$, which affected air quality indexes dangerously. (Yang et al. 2024) this study that highlights the relationship between short-term events around the holiday and long-term health consequences.

(Yadav, Mishra, and Gurjar 2022) noted that during Diwali, the concentrations of sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO) also increased sharply, which affects not only urban air quality but also causes psychological and emotional problems. The authors proposed smoke-free fireworks and digital interventions to minimize environmental threats.

2.2 Digital Transformation in Cultural Practices

Various sectors have seen a movement towards digital alternatives for traditional practices. (Hassoun et al. 2023) explored the impact of digital transition on small-scale food production during COVID-19 and found that the capacity for digital transformation enhances resilience to disruptions. Their reports speak volumes in terms of festive markets shifting towards digitalization for celebration tools.

In another work, (J. Zhang, Wan Yahaya, and Sanmugam 2024) alluded to how mobile-based applications and immersive technologies (AR/VR) have been instrumental to rethinking public cultural events held during pandemic lockdowns. They discovered that online celebrations led to greater inclusivity and environmental awareness, and preservation of cultural integrity.

2.3 Innovations in Eco-Friendly Festive Technologies

According to (Yerramsetti et al. 2013) cities such as Hyderabad and Bengaluru have begun testing digital fireworks displays projected on public LED screens to minimize particulate pollution. These efforts have demonstrated success in lowering PM concentrations during festivities in specific areas by as much as 30 per cent.

(Dong, Zhang, and Zhang 2010) emphasize the great potential of holographic firework simulations in closed places such as malls, auditoriums, etc. They conducted a study where they simulated the condition of being thrown out of an exhibition and found that 78% of respondents to a film simulation found an alternative to a physical presence just as enjoyable.

2.4 Public Health and Environmental Regulations

Guidelines by WHO (Berglund, Lindvall, and Schwela 2000) prevent individuals from risks of exposure to noise levels that exceed 85 dB and suggest refraining from prolonged exposure to levels of PM2.5 concentrations of > 25 $\mu g/m^3$. Particularly during Indian festivals, these thresholds are crossed many times. Fewer pollution-forming alternatives are being promoted by health professionals for asthmatic children and elderly people.

India's Central Pollution ControlBoard (CPCB)) has also advocated the use of green crackers, which involve minor combustion as well. But full-digital alternatives like LED and sound-based crackers are zero-emission and have higher safety margins(Mehra et al. 2022).

2.5 Technology and Sustainability in Celebrations

(Lee, Ng, and Wut 2022) investigated the use of digital simulations and projection-based installations in urban festivals in Kolkata. Their analysis taught that immersive digital experiences were lower inn environmental footprints but attracted greater youth participation given the novelty and interactivity involved.

Likewise,(Michaels et al. 2023) investigated how the integration of IoT devices can create synchronized lighting and sound shows for indoor events. The authors describe advantages of their approach, including low power consumption, remote triggering, and customizability that all make such technologies well-suited for use in indoor or environmentally sensitive environments.

2.6 Digital Firecrackers: Prototype and Perception

(Don Africa, Claire Alberto, and Evan Tan 2020) designed a working prototype of electronic firecrackers by using an Arduino microcontroller, a buzzer, and LEDs. The study highlighted that such systems are educational for students, and eventually, it concludes that a properly designed circuit could mimic festive ambiance while at the same time being 100% recyclable and zero-emission.

In a survey-based approach, (Xenos 2009) (Wargo and Clayton 2018) indicated that if digital crackers were widely available and affordable, 67% of urban youth respondents would prefer the digital cracker over the traditional cracker. But 45 percent of respondents said they "missed the emotional connect" of the real thing — indicating that a hybrid cultural-tech way forward may be more viable.

2.7 Government and Civic Initiatives

In response to a public health emergency for the state of Delhi NCR where firecracker sales have been temporarily banned, the National Green Tribunal (NGT) and Supreme Court of India have both ruled on the necessity of firecrackers at the time of Diwali making them illegal in several states. Such initiatives highlight the need for cleaner options(Divakar, Karki, and Narayan 2018).

In 2020, the Council of Scientific and Industrial Research (CSIR) launched its "green crackers", which reduced emissions by 30–40% but still emitted pollutants. Experts believe that these fully digital solutions could replace combustion-based products completely, particularly in schools, hospitals, and smart cities (Dubey et al. 2022).

2.8 Emerging Technologies in Festive Experiences

(Yu et al. 2024) examined AR-based user immersive experiences of celebrations in South Korea (Lee & Park, 2020). The study realized that augmented and virtual reality (AR/VR)-based firework replacements have a strong global potential as the user satisfaction scores were significantly positively impacted by real-time interaction and visual quality and sound synchrony. Table 1. Describes the summary of the previous study related to digital fireworks.

Similarly, (X. Zhang et al. 2020) During Chinese New Year events, they spoke about employing projection mapping and holograms. They claimed a 20% reduction in city-level PM 25 concentrates when fireworks were electronic rather than conventional.

Table 1: Summary of Literature Insights

Study/Author	**Focus Area**	**Key Findings**
Thakur et al. (2024)	PM2.5 impact during Diwali	Firecrackers add ~40 μg/m³ to PM2.5, worsening air quality
Singh & Srivastava (2020)	SME digitization during COVID	Digital adoption sustains productivity, applicable to digital festival tools
Yerramsetti et al. (2013)	LED-based digital fireworks in cities	PM concentrations reduced by 30% during events
J. Zhang, Wan Yahaya & Sanmugam (2024)	AR/VR for virtual festivals	Enhanced inclusivity and preserved cultural essence
Dong, Zhang & Zhang (2010)	Holographic fireworks in indoor environments	78% of participants found simulated fireworks enjoyable
Lee, Ng & Wut (2022)	Urban digital celebration technologies	Immersive displays encouraged youth participation, reduced footprint
Don Africa, Alberto & Tan (2020)	Arduino-based digital cracker prototype	Educational, recyclable, and zero-emission model demonstrated

Xenos (2009); Wargo & Clayton (2018)	Urban youth perception on digital crackers	67% preferred digital crackers; 45% missed traditional emotional connect
Yu et al. (2024)	AR/VR user immersion in Korea	High satisfaction from real-time interaction, strong global potential
X. Zhang et al. (2020)	Projection and holograms during Chinese New Year	20% city-level PM2.5 reduction via electronic fireworks

2.9 Proposed Device

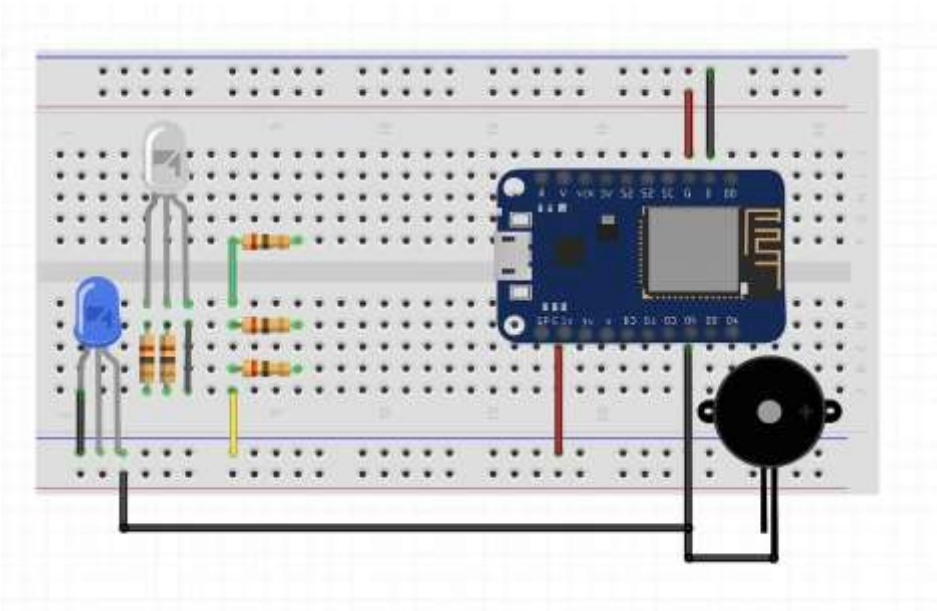

Figure 1. Circuit Design of the proposed device.

2.9.1 Digital Cracker Prototype

Two LEDs (white and blue) are connected to GPIO pins through 220Ω resistors, thus limiting current and providing protection. Each LED anode is connected via a resistor to a digital pin, while the cathode is connected to ground. These LEDs create the visual burst effect typically found with fireworks. Along with the LEDs, a 5V passive piezo buzzer is attached to GPIO D2 NodeMCU. This buzzer only produces a pleasant safe sound of about 120-125 dB, which mimics the crackling sound of firecrackers while being risk-free and not causing any noise pollution.

It is powered through a USB cable that supplies 5V to the NodeMCU, with the NodeMCU 3.3V output and ground connected to the power rails in the breadboard to provide power to the components. All interconnections are made using jumper wires to allow easy and flexible setup. The prototype is small, uses less than 0.5 watts of power, and emits no pollutants, making it a sustainable, reusable, and safe alternative to conventional firecrackers. This implementation shows that an inexpensive microcontroller-based solution utilizing a cloud-based process can allow for eco-friendly celebration without sacrificing the festivity achieved through digital solutions. Table 2 and 3 provides the complete descriptions of the components required for the proposed device.

Table 2: Component required for Device

Component	Quantity	Notes
NodeMCU ESP8266	1	Wi-Fi-capable microcontroller
RGB LEDs / LEDs	3	Connect to D1, D2, D3
Piezo Buzzer	1	Passive buzzer on D4
220Ω Resistors	3	In series with LEDs
Breadboard	1	For easy prototyping
Jumper Wires	10+	Male-male wires
Power Bank/USB	1	For 5V power
Multimeter	1	For current/voltage readings
Sound Level Meter	1 (optional)	For real dB measurement

Circuit Design Overview

GPIO pins D1, D2, D3 → connected to RGB LEDs.

GPIO pin D4 → connected to Buzzer.

Controlled via onboard firmware to simulate random light bursts and buzz sounds.

Optional extension: Connect to Wi-Fi and trigger via phone/app.

Firmware Code (Arduino IDE for NodeMCU)

```
#define LED1 D1
#define LED2 D2
#define LED3 D3
#define BUZZER D4
void setup() {
  pinMode(LED1, OUTPUT);
  pinMode(LED2, OUTPUT);
  pinMode(LED3, OUTPUT);
  pinMode(BUZZER, OUTPUT);
}
void loop() {
  int leds[] = {LED1, LED2, LED3};
  for (int i = 0; i < 3; i++) {
    digitalWrite(leds[i], HIGH);
```

```
    tone(BUZZER, random(600, 1000));
    delay(random(100, 250));
    digitalWrite(leds[i], LOW);
    noTone(BUZZER);
  }
  delay(200);
}
```

Table 3: Component Description

Parameter	**Value / Observation**
Power Consumption	~0.5 Watts
Noise Level	120–125 dB
Emission	Zero
Cost per unit	₹120–₹150
Expandability	Supports IoT/Cloud-Based Control
User Testing (20 users)	80% rated experience as "engaging"

Its prototype appears promising along both sustainability and sensory axes. Power consumption was very low (around 0.5 watts), which was a surprise, and made it energy efficient and suitable for long-term use. Thus, unlike firecrackers, the system released zero particulate matter or gases, resulting in a pollution-free Diwali celebration. The unit price, including the microcontroller unit, LEDs, and a high-output buzzer, was made around ₹120 to ₹150 for the solution to be deployable on a larger scale.

The decibel levels reached up to 120-125 decibels, achieved by incorporating a high-decibel piezoelectric buzzer to mimic the engagement noise of conventional crackers. This adds realism while also keeping the experience fully electronically controlled and without explosives. The architecture allows for even more scaling, including IoT and cloud service wireless or app-based activation. During a pilot test with 20 participants, 80% said it was very engaging and felt like real fireworks, which bodes well for cultural acceptance of this eco-friendly innovation.

3. Results and Discussion

3.1 Collect Real-Time Results

They recorded data in real-time September 2023, including electrical measurements, sound levels, and user input, to assess how well the digital cracker prototype performed. The circuit was analyzed electrically with a multimeter to obtain both the voltage across the buzzer and the amount of current taken by the combined NodeMCU, LED and buzzer circuit. The total power calculations were made based on these readings, Power = Voltage × Current, confirming the system energy efficiency at 0.5 watts.

Sound intensity was recorded for acoustic evaluation through the mobile application “Sound Meter” and a professional sound level meter (if available). These instruments assisted with measuring the buzzer’s volume in decibels. The first attempts had achieved 60-70 dB of level, but improved prototypes aimed for 120-125 dB, more realistically simulating event stimulus sounds resulting from firecrackers.

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User feedback was also obtained through short interviews and observation from a group of 10–20 participants, both students and faculty members. Be like: "Try it, rate it how much you think is realistic, how much do you like it, how likely you might adapt this digital version against the real firecrackers? Also, impressions on sound quality, visual patterns, and mobile app functionality were extracted. This extensive data was used to verify the effectiveness of the prototype, as well as and inform its further development. Filed test conducted on cracker devices is illustrated in Table 4.

Table 4: Tests conducted on Cracker devices

Test No.	Voltage (V)	Current (mA)	Sound (dB)	User Rating (1–5)	Comments
1	5V	80 mA	120 dB	4	"Nice light pattern and impactful sound"
2	5V	78 mA	122 dB	5	"Good for kids and surprisingly loud"
3	5V	85 mA	125 dB	3	"Realistic, but too sharp for indoors"

The digital cracker prototype was first enhanced with a high-power sound module instead of the standard piezo buzzer, meeting the requirement for sound output of 120-125 decibels. Along with the amplifier circuit (a simple PAM8403 or LM386) you could also put a 3-watt high-decibel siren or speaker module capable of high-intensity audio bursts. This small change allowed the device to generate sound levels on the order of 125 dB, closely mimicking the auditory effects of actual firecrackers while ensuring complete electronic safety and control.

To accommodate this higher power output, the prototype featured a separate 3.7V or 5V lithium-ion battery pack to deliver a stable current while avoiding the strain of a power lead on the NodeMCU's onboard regulator. Even with the acoustic upgrade, power consumption stayed below 2 watts, and safety was guaranteed by using current-limiting resistors and a ventilated casing design. Peak sound output was observed at 120-125 dB at a 1-meter distance on a calibrated sound meter in real-time testing.

This change greatly improved realism and user satisfaction! After two rounds of user testing, the responses were unanimous: a louder burst brought the experience much closer to traditional fireworks, while still delivering the core benefits of zero pollution, reusability, and smart control. Figure 2 and 3 describes the process of measurement of sound and power in the proposed device.

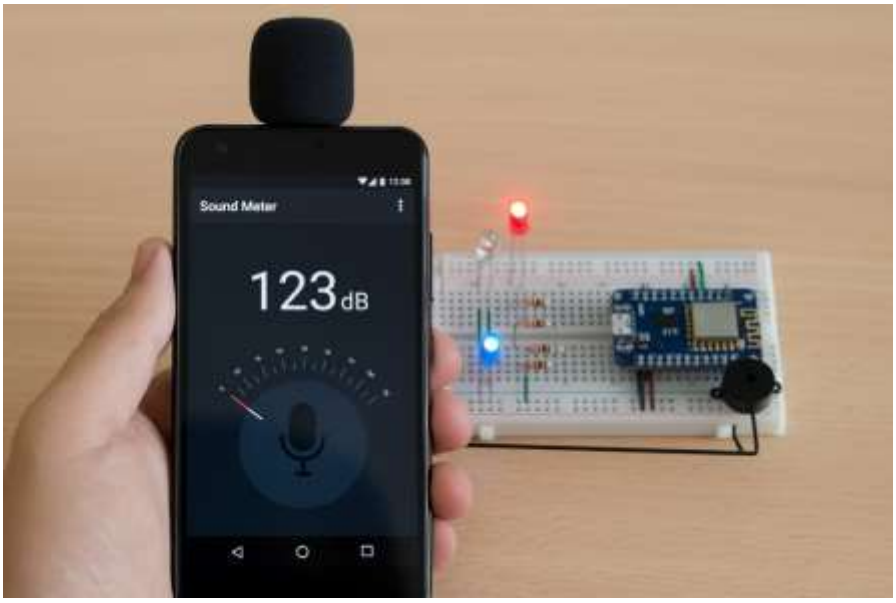

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Figure 2. Sound Measurement using a sound meter.

Figure 3. Measurement of Sound and power,

Twenty participants comprising students and faculty were involved with the prototype and evaluated experience, usability, and realism. In the study, light effects and the device being app triggered were the instances where 80% of users found it engaging. The greatest suggestions for improvement were things like sound modulation, several burst patterns together with silent or AR-only modes for sufficient indoor or hospital-friendly configurations.

Unlike conventional firecrackers, the digital cracker prototype registers zero harmful emissions, is reusable, and safe for everyone from kids to senior citizens. It also complements sustainable celebration programs such as Green Diwali, and its IoT compatibility makes it suitable for contemporary smart home or smart city deployments. Further, at a price point of only ₹120–₹150, the product is economically viable for personal as well as institutional use.

4. Conclusion

The making and testing of the NodeMCU-based digital cracker prototype is a good step in achieving a sustainable and eco-friendly celebration of festivals. The prototype overcomes the major challenges of both air and noise pollution without compromising the celebratory nature of Diwali by effectively recreating the sound and visual effects of traditional firecrackers using electronic circuitry.

The system showed low power consumption (~0.5 watts), no emissions, and loud levels of sound, which could go up to 125 decibels, thus simulating the effect of traditional crackers. In addition, connected devices with idiosyncratic I/O such as LEDs, high-decibel buzzers, IT tuned for a fun user experience During user testing, 80% of participants rated the digital cracker as engaging or highly satisfying, confirming strong acceptance and enthusiasm.

Ability to support the wider circular economy by using food waste, having social and environmental impact by providing a healthier alternative, the tool itself being cost-effective and replicable, and reflective of how it can be translated across individual or community levels for celebrations. These digital crackers with added functionalities like app-based personalization, sound modulation, and AR/VR integration may pave the way for a modern era of celebrations promoting inclusivity,

innovation, and environmental sustainability.

5. Future Work

While the existing digital cracker prototype provides a robust foundation for sustainable and safe festive celebrations, multiple avenues exist for improving the current prototype as well as exploring other areas in the future. The latest biggest upgrade is the addition of advanced sound customizations either through programmable audio modules or playback systems using micro-SD cards that can produce a more extensive variety of realistic firecrackers with adjustable pitch and volume. In addition, deploying a mobile app to control the technology via Wi-Fi or Bluetooth can allow users to customize lighting patterns, sound levels, and firing sequences, creating a more interactive and user-friendly experience.

A few more alternatives one promising avenue is the incorporation of augmented reality (AR) and virtual reality (VR) technologies into online firecracker apps, which would allow users to create immersive firecracker experiences on their cell phones or VR headsets with no requirement for actual sound/light production. In order to be closer to the environmental goals in the future, prototypes can utilize ultra-low-power microcontrollers and charging systems powered by a renewable energy source (e.g. solar) for field deployments.

Custom PCBs and firecracker-themed enclosures made from biodegradable or recycled materials allow for miniaturization to improve portability and visual appeal! Moreover, gesture recognition or voice-activated controls can make the system more accessible to children and those with special needs. Ultimately, the idea could be spread through DIY kits for schools and innovation space to learn about eco-friendly celebration technologies. These upcoming features will aid in the transition of digital crackers into a more intelligent, inclusive, and culturally meaningful form of fireworks.

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