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Trends in laser marking technology for agricultural products in Africa

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Abstract: Product marking is very important as it provides information about the product through the agricultural value chain without the information being missing or tampered with. Therefore, it is necessary to use technologies that would permanently mark agricultural products, and one such technology is laser marking. This technology is being explored and used in other parts of the world, such as Europe, Australia, and the United States, intensively in the agriculture sector. However, in Africa, it has been used in only a few countries such as South Africa, Kenya, and Nigeria. There is a need to encourage, educate, and sensitize people on the beneficial effects of its use, such as high precision of work, permanent marking, high resistance to external effects like heat and abrasion, low power consumption, and being environmentally friendly. Therefore, this paper seeks to review the trends of laser marking of agricultural products in Africa and also provide recommendations on its use, especially in Ghana.

Keywords: Laser marking technology, Direct part marking, Traceability, Product marking.
Abbreviations: DPM_Direct part marking; RFID_Radio-frequency identification; GDP_Gross Domestic Product; CAADP_Comprehensive Africa Agriculture Development Programme; SMEs_Small and medium-sized enterprises; IoT_Internet of Things; AI_Artificial Intelligence.

Introduction

Agriculture remains a cornerstone of Africa's economy, serving as a key driver of Gross Domestic Product (GDP), employment, and food security. Despite its foundational role, the sector grapples with several persistent hurdles such as limited market integration, low output efficiency, and considerable post-harvest losses (Langyintuo, 2020). In recent times, emerging technologies have been increasingly recognized for their transformative potential to address these issues and strengthen the agricultural value chain (Saikanth et al., 2024).

A crucial aspect of enhancing agricultural efficiency lies in the capacity to trace and monitor produce throughout the supply journey from cultivation to consumption (Eyahanyo & Rath, 2020; Kang & Lee, 2013). Accurately marking products helps safeguard against theft and tampering while facilitating the seamless flow of information about origin and quality (Eyahanyo & Rath, 2020; Kang & Lee, 2013; Kemény, Bozóki, Ilie-Zudor, & Monostori, 2014; Tekin, 2014; Ventura et al., 2016). Technologies like barcodes and RFID tags have traditionally fulfilled this role, but each has limitations. Barcodes are susceptible to removal or degradation, and RFID tags can be disrupted by environmental elements such as water or metal surfaces (Bassoli, 2018; Eyahanyo & Rath, 2020).To overcome these limitations, more robust solutions such as direct part marking (DPM) have gained traction. DPM refers to techniques where identifiers are permanently embedded on a product's surface (Bassoli, 2018; Denkena, Grove, & Seibel, 2016; Eyahanyo & Rath, 2020; He & Joseph, 2017; Li et al., 2016; Ventura et al., 2016). Among the DPM methods, laser-based marking technologies also referred to as laser etching or branding stand out for their precision and durability. These systems enable producers to inscribe vital data such as harvest date, geographical origin, and quality indicators directly onto products or packaging without compromising product integrity (Nadimi, Sun, & Paliwal, 2021; Sanchez, Hashim, Shamsudin, & Nor, 2020). Laser marking supports traceability systems that span the entire supply chain, promoting food safety, ensuring quality standards, and improving access to premium markets (Prashar, Jha, Jha, Lee, & Joshi, 2020).

Africa's agricultural landscape is marked by a rich diversity from smallholder farms to large commercial enterprises. For over 60% of the population, agriculture is the main source of livelihood, and it accounts for roughly 23% of the GDP in Sub-Saharan Africa (Jayne et al., 2019; Shimeles, Verdier-Chouchane, & Boly, 2018). Even in the face of climate change, infrastructural constraints, and market accessibility challenges, the sector has continued to show potential for resilience and sustained growth (Semeraro, Scarano, Leggieri, Calisi, & De Caroli, 2023). Beyond subsistence, agriculture is pivotal to trade and foreign exchange earnings across the continent (Shimeles et al., 2018).

Traceability, in this context, pertains to the ability to document and follow the product's lifecycle, offering critical insights into its origin and handling. In global food supply systems, traceability has become indispensable not only for ensuring food safety and quality but also for meeting stringent international market requirements (Bai et al., 2017; Salah, Nizamuddin, Jayaraman, & Omar, 2019). This, in turn, creates new economic pathways for African producers by supporting regulatory compliance and unlocking exports (Francois, Fabrice, & Didier, 2020; Karki, Fasse, & Grote, 2016).

Laser marking works by harnessing focused beams of light generated through stimulated radiation to etch permanent identifiers onto product surfaces (Etxeberria, Narciso, Sood, Gonzales, & Narciso, 2009; Eyahanyo & Rath, 2020; Marx, Hustedt, Hoja, Winkelmann, & Rath, 2013; Nasution & Rath, 2017; Pullman, 2017; Sobotova & Badida, 2017). Unlike traditional ink-based or mechanical methods, laser systems offer contactless, precise, and environmentally sustainable solutions with superior longevity and clarity (Etxeberria et al., 2009; Eyahanyo & Rath, 2020; Marx et al., 2013; Nasution & Rath, 2017; Pullman, 2017; Wlodarczyk et al., 2017). Their application in agriculture extends beyond marking; laser technology also aids production through techniques such as laser bio-stimulation and spectral analysis methods like Raman spectroscopy (Nadimi et al., 2021). Moreover, two-dimensional laser barcodes have already shown promising applications in wood product traceability, reinforcing the broader viability of this method across agricultural contexts (Nadimi et al., 2021).

This review explores how laser marking is being integrated into Africa's agricultural ecosystem. It examines the core principles of the technology, ongoing trends, specific applications, and the potential benefits and limitations associated with its use. By showcasing relevant case studies and discussing future outlooks, the review aims to offer valuable insights for farmers, agribusinesses, policymakers, and technology providers looking to strengthen traceability, ensure product integrity, and improve competitiveness in domestic and international markets.

Historical Development of Laser Marking Technology

The journey of laser marking technology began in the 1960s, shortly after the laser itself was first introduced (Boulon, 2012). Initially harnessed for scientific research and defence applications, its industrial potential quickly became evident (Gu, 2006). The development of CO_2 lasers in the 1970s and the subsequent emergence of Nd: YAG lasers in the 1980s marked pivotal moments in expanding laser applications across industries (Hall, 2021; Ireland, 1992). These innovations laid the groundwork for broader adoption. Towards the end of the 20th century, fibre lasers emerged, offering improvements in speed, cost-efficiency, and versatility, particularly for marking on diverse surfaces (Angelova, Mežinska, & Lazov, 2017).

At its core, laser marking employs a beam of concentrated light to induce surface changes on a target material (Weidenfeller et al., 2019). Depending on the substrate and intended effect, the process might involve surface annealing, carbon migration, foaming, ablation, or colour alteration (Amuda & Akinlabi, 2016; Kusinski et al., 2012). Adjustments to laser power, beam speed, frequency, and focal distance allow for high-precision markings with varied depths and patterns (Amuda & Akinlabi, 2016; Kusinski et al., 2012).

Conventional techniques such as ink printing, stamping, and mechanical engraving have long served product marking needs. However, laser marking stands out for several compelling reasons:

- **Precision and Information Density**: Laser systems can produce extremely detailed and compact markings, which are essential for traceability and serialization (Weidenfeller et al., 2019).

a. **Contact-Free Operation**: Unlike traditional methods, the laser beam doesn't touch the product surface, minimizing the risk of mechanical damage or contamination (Papernov & Schmid, 2008).

b. **Durability**: Laser-etched codes withstand environmental exposure and mechanical wear, supporting long-term readability (Bakhtiyari, Wang, Wang, & Zheng, 2021).

- **Material Versatility**: This technology is compatible with a wide range of materials from metals and plastics to glass and even organic items like fruits and vegetables without the need for inks or consumables (Yang, Fu, Wang, Luo, & Yao, 2022).
- **Eco-Conscious Processing**: Since it eliminates the use of chemicals and minimizes waste, laser marking is a cleaner and greener alternative to traditional labelling methods (Javaid, Haleem, Singh, Suman, & Gonzalez, 2022).

In agriculture, these advantages have catalyzed the shift toward laser-based product identification, offering a sustainable, efficient, and resilient solution for improving traceability.

The transition to laser marking technology in the agricultural sector is driven by these advantages, addressing the growing need for efficient, reliable, and sustainable methods for product identification and traceability.

Laser Marking Setup Overview

For the laser coding of the ECC200 Data Matrix on fruit surfaces, a Synrad 48-5 CO_2 laser (Synrad Inc., Mukilteo, USA) operating at a wavelength of 10600 nm and a power output of 50 W was used. The system, running at 380 mm/s, is equipped with a SH3-200C scan head and controlled through WinMarkPro® software on a PC. The experimental layout consists of key components: a CO_2 laser source, a computer-regulated marking head, a manual lifting mechanism for product positioning, and a control unit. The laser beam, focused and guided by the scan head, is fine-tuned via computer settings

that define marking depth, speed, and precision. Product height is adjusted manually using a lifting table to ensure optimal marking focus at 246 mm. A universal controller synchronizes system components, while a dedicated water-cooling module maintains thermal stability during extended use. The system draws 30 VDC from its power supply and is semi-automated relying on manual handling for placing and retrieving marked items. Conveyor integration is currently absent (Figure 1).

Laser Marking Technology in Agriculture

Laser marking is making significant strides in the agricultural industry by enhancing product identification, traceability, and branding strategies (Nadimi et al., 2021). Originally confined to industrial applications, this technology is now being successfully applied to agricultural commodities like fruits, vegetables, and even livestock. Its adoption promises a range of benefits, including improved efficiency and sustainability (Table 1). Moreover, the textile sector has started replacing environmentally harmful marking methods with laser engraving (Evans, 2006). In the postharvest handling of agricultural goods, laser imaging has emerged as a promising non-destructive assessment tool (Mollazade, Omid, Tab, & Mohtasebi, 2012). In response to marking challenges in food-grade plastic materials, researchers have engineered laser systems that ensure safe, high-speed marking without relying on chemical additives (Mollazade et al., 2012). When deploying laser marking in agriculture, the chosen system must align with the product type, environmental conditions, and specific production needs. Commonly used laser types include:

- **CO_2 Lasers**: These are particularly effective for organic and non-metallic surfaces, making them ideal for marking items like fruits and vegetables. They create clear, legible marks without damaging the product itself (Eyahanyo & Rath, 2020; Marx et al., 2013; Nasution & Rath, 2017; Puértolas, Pérez, & Murgui, 2023).
- **Fibre Lasers**: Preferred for metal marking, fibre lasers are used on agricultural tools and machinery. They deliver durable, high-contrast marks that can endure harsh conditions (Kliner & Victor, 2019).
- **UV Lasers**: Though not typically applied to fresh produce, UV lasers are excellent for marking packaging materials, especially those that are heat-sensitive (Sanchez-Jimenez & Salais-Fierro, 2021).

To cater to the practical realities of agricultural environments, laser technology has been tailored with specific solutions:

- **Conveyor-Based Systems**: These allow for automated, high-speed marking of produce, greatly benefitting operations that process large quantities (W. Zhang, Xiao, & Yan, 2021).
- **Portable Units**: For livestock or large machinery, mobile laser devices offer the versatility needed to mark items directly in the field or on-site (Ehlert, Heisig, & Adamek, 2010; Trotter, 2010).
- **Flexible Configuration**: Laser settings such as power levels, marking speed, and beam focus—can be adjusted to suit different product types and ensure safe, effective marking (Kalita, Shivakoti, & Ghadai, 2017; Lazov & Petrov, 2013).
- **Food-Safe Marking**: In cases where the laser is used directly on food surfaces, the process is calibrated to affect only the outer skin, preserving safety and quality (Miteluț et al., 2021).
- **Integration with Packaging Systems**: Many modern facilities link laser marking tools with sorting and packaging lines to reduce labour needs and boost workflow efficiency (W. Zhang et al., 2021).

Adopting laser marking in agriculture brings various strategic advantages:

- **Improved Traceability**: Laser-etched identifiers allow products to be tracked accurately through the supply chain, aiding in food safety and compliance (Opara, 2003).
- **Eco-Friendly Labelling**: By enabling direct-on-product marking, the need for extra packaging materials is eliminated, supporting sustainability goals (Ma, Aranda-Jan, & Moultrie, 2019).
- **High Productivity**: These systems can mark hundreds of items per minute, significantly improving processing times and throughput (D. Wang, Yu, & Zhang, 2015).
- **Lasting Marks**: Unlike stickers or ink, laser marks do not wear off easily, even in extreme conditions, maintaining their visibility throughout the product's journey (Wlodarczyk et al., 2017).
- **Branding Potential**: Companies can engrave their logos or unique identifiers directly onto products, strengthening brand identity and customer recognition (Ming, Hoult, & Tse, 2008).

Laser setup

The Synrad 48-5 carbon dioxide laser, Synrad Inc., Mukiltoe, USA, with wavelength 10600 nm, output power 50 W, speed 380 mm/s, and SH3-200C marking head controlled by a PC (personal computer) and the laser marking software (WinMarkPro®, Synrad Inc., Mukiltoe, USA) has been used for marking ECC200 Data Matrix codes on fruits. Laser marking experimental setup illustrating the main components: CO_2 Laser (Synrad 48-5), Marking Head, Product Positioning System, and Computer-based Control Unit. The CO_2 laser generates a focused laser beam directed through the marking head (specific manufacturer/model should be added here), precisely controlled by a computer system responsible for laser beam adjustment and marking parameters. Product positioning is manually assisted using a lifting table mechanism designed for adjusting the height of the product to an optimal marking distance (246 mm). A Universal Controller is integrated for system coordination, and a dedicated water-cooling system ensures stable laser operation by managing heat dissipation. The power supply unit provides 30 VDC to the system. This setup is semi-automatic, as manual labour is required for positioning and adjusting the product height. The current design does not include a belt conveyor and product placement and removal are handled manually (Figure 1).

Comparative Analysis of Laser Marking, Inkjet, and Adhesive Labelling Techniques

Laser marking, inkjet printing, and adhesive labelling are three prevalent technologies applied across industries for purposes like product traceability, identification, and branding. Each method is technically distinct and offers specific advantages and limitations depending on the application context. Laser marking utilizes a focused laser beam to create permanent surface modifications, ideal for encoding data such as barcodes, serial numbers, logos, or text directly onto a substrate (Hoekstra et al., 2008). In contrast, inkjet systems work by projecting ink droplets onto surfaces to form printed text or graphics, while adhesive labelling involves affixing pre-printed or dynamically printed labels using sticky backings (Han & Gubencu, 2008). Deciding which method to use typically depends on factors like the nature of the materials, required production speed, cost constraints, durability of the markings, and environmental considerations.

Laser marking stands out particularly for its robustness. Since the markings are etched into the material, they resist degradation from chemical exposure, heat, and physical wear attributes that make laser ideal for demanding sectors such as aerospace, automotive, and healthcare manufacturing (Roozbahani et al., 2020). Another advantage is the lack of ongoing consumable costs, such as ink or labels, which not only reduces long-term maintenance but also supports environmentally conscious production. Laser systems also produce extremely precise and high-definition marks, even for intricate designs. However, the initial cost of laser equipment is relatively high, and not all materials especially heat-sensitive ones are compatible with this technique (Jacob et al., 2023).

Inkjet printing, on the other hand, is valued for its speed and adaptability. Continuous inkjet (CIJ) technology functions efficiently across a broad spectrum of substrates, including metals, plastics, paperboard, and glass, making it versatile for varied industrial uses (Yesuf et al., 2023). Inkjet printers generally come with a lower purchase price compared to laser units and allow for quick changes in the data being printed, which is useful for batch and date coding. However, their printed outputs are less durable and may fade or smudge when exposed to moisture or solvents. Additionally, inkjet systems incur recurring expenses for consumables like ink and cleaning agents, along with routine maintenance (Castrejon-Pita et al., 2013; Heilmann & Rusko, 2010).

Adhesive labelling, often considered the most conventional method, remains widely used due to its versatility across various shapes and surfaces. This approach supports comprehensive information display, including detailed product data, branding elements, barcodes, and QR codes making it especially relevant for the food, pharmaceutical, and retail sectors (Kurek, 2021). Labels can be produced in bulk or customized individually as needed, offering great design and branding flexibility. However, environmental exposure can lead to issues like label peeling, fading, or tearing. Moreover, the equipment required for label application can be mechanically intricate, needing regular adjustment to maintain reliability (Weigelt et al., 2010).

From a cost perspective, inkjet and adhesive labelling systems usually require less capital investment upfront. Nevertheless, the operational costs can accumulate significantly due to the ongoing need for consumables and maintenance. Laser marking, while more expensive initially, often proves more cost-effective in the long run, particularly in settings with high production volumes due to its low running costs and minimized need for rework (Zhou et al., 2024). The permanence of laser inscriptions also reduces the risk of relabeling, which can arise from damage or wear (Zhou et al., 2024).

When it comes to environmental impact, laser marking is notably sustainable. It eliminates the use of inks, solvents, and adhesives, all of which contribute to industrial waste and require careful handling and disposal. This makes laser a strong candidate for companies with green manufacturing goals (Sobotova & Badida, 2017). Conversely, inkjet and adhesive techniques generate more waste through the consumption of ink cartridges and label backings. Their environmental footprint is larger and requires active waste management protocols (Nath et al., 2019).

In conclusion, the decision between laser, inkjet, and adhesive labelling should be informed by a thorough understanding of the operational environment and goals. Laser marking excels where permanence, precision, and eco-friendliness are top priorities (Shao et al., 2024). Inkjet printing is best suited for applications demanding fast, flexible printing capabilities, though it may fall short in durability. Adhesive labelling remains a go-to for high-quality visual appeal and information-rich designs in consumer-facing products. Ultimately, the choice should align with production needs, environmental policies, and long-term cost-effectiveness (Hoekstra et al., 2008).

Emerging Trends in Laser Marking Across Africa

The integration of laser marking technology within African agriculture presents a diverse picture, shaped largely by regional differences in economic capacity, technological infrastructure, and supportive policy environments. Countries like South Africa, Kenya, and Nigeria, which exhibit relatively advanced agricultural systems and better access to innovation, are at the forefront of adopting laser marking tools. These nations are leveraging the technology to improve traceability, enhance quality assurance, and gain a competitive edge in both local and international markets.

South Africa's Citrus Sector

A prime illustration of laser marking implementation is found in South Africa's globally recognized citrus export industry. According to (Ampatzidis, 2019), the sector adopted laser etching to streamline traceability and reduce reliance on non-biodegradable packaging materials. By inscribing traceability and branding details directly onto the citrus peel, producers have managed to bypass the traditional use of adhesive labels. This advancement not only reduced environmental waste but also helped producers meet the rigorous traceability and quality benchmarks demanded by international buyers, especially in the EU and Asia (Evans, 2006).

This form of marking employs finely tuned laser beams to imprint shallow, non-invasive information such as logos, batch codes, and QR codes on the fruit surface. The markings do not compromise the fruit's integrity or edibility. Processing typically occurs post-harvest; as fruits travel along sorting lines, they pass beneath automated laser heads that apply

consistent, tamper-proof, and weather-resistant labels (Nasution & Rath, 2017; Khadka et al., 2024). These features are particularly valued in export markets that require stringent product tracking mechanisms.

Kenya's Tea Industry

Kenya's tea trade, another pillar of African agricultural exports, has also benefited from laser-based marking solutions. With growing concerns over product counterfeiting and quality disputes, the industry began using laser engraving to apply secure identifiers to packaging materials (Chen et al., 2012). These identifiers often comprising batch details, manufacturing dates, and scannable QR codes help verify authenticity and trace each tea package through the entire supply chain (Bank, 2018).
Instead of marking the tea leaves themselves, producers focus on the packaging such as foil-wrapped boxes and kraft sacks. The marks, which are made during the packaging phase in factories or cooperatives, integrate with digital traceability systems. Some producers have even linked these codes to blockchain platforms, allowing end-users to verify origin and quality via mobile devices (Hoekstra et al., 2008; Liao & Xu, 2019). This process has greatly strengthened Kenya's global brand presence and reassured consumers in markets like Europe and the Middle East, where product origin and legitimacy are closely scrutinized.

- Nigeria's Agricultural Equipment Tracking:

In Nigeria, laser marking has been adopted in a slightly different context tracking agricultural machinery and tools. Faced with persistent challenges like equipment theft and inventory mismanagement, stakeholders turned to laser engraving as a solution for long-lasting identification and asset monitoring (Elijah, Orikumhi, Rahman, Babale, & Orakwue, 2017). Metal parts of tractors, irrigation systems, and other farm implements are marked with data such as serial numbers, owner IDs, and even GPS-linked identifiers. These engravings are highly durable and designed to resist environmental stressors like UV radiation, moisture, and wear (Shariati et al., 2010; Ganzulenko & Petkova, 2020). Markings are typically applied during equipment acquisition or distribution phases, often through partnerships with extension services. Some regions also maintain central digital registries that link engraved IDs to ownership and maintenance histories, accessible via mobile platforms enhancing transparency and accountability in government or cooperative-run equipment schemes.

Technological Integration and Future Prospects

Laser marking is increasingly being embedded in broader digital ecosystems to maximize its utility. For instance, its synergy with precision agriculture tools and Internet of Things (IoT) devices allows for meticulous tracking of inputs and yields, improving decision-making and reducing waste (Elijah et al., 2017). Additionally, integration with blockchain systems ensures that traceability records are immutable, promoting trust throughout the food value chain (Prashar et al., 2020; X. Yang et al., 2021).
Looking ahead, the role of laser marking in transforming African agriculture is expected to grow, driven by technological progress and rising awareness of its economic and environmental advantages. Scaling up will require not just technology adoption but also enabling policies and investment in infrastructure. With the right support, laser marking could become a standard practice across the continent helping producers meet global standards, reduce waste, and improve overall value chain efficiency.

Applications of Laser Marking in Agricultural Products

Laser marking technology has increasingly gained ground in agriculture, largely due to its adaptability, precision, and eco-friendly characteristics. Its use now spans several critical points in the agricultural value chain from initial production to retail distribution. Specifically, laser marking has found practical value in the labelling of fresh produce, livestock tagging, packaging customization, branding, and regulatory compliance (Table 1).

- **Etching of Fruit and Vegetable**

A notable advancement in this field is the direct laser etching of fruits and vegetables. This technique involves the safe removal of the outer layer of produce to inscribe traceability information, branding logos, or consumer-facing messages, without altering the taste or shelf life of the items (Etxeberria, Miller, & Achor, 2006; Eyahanyo & Rath, 2020; Marx et al., 2013; Nasution & Rath, 2017). For example, citrus fruits and avocados are now etched with data instead of using plastic stickers, aligning with sustainability efforts (Bower & Dennison, 2003). In countries like South Africa, this method has also supported efforts to reduce environmental waste from packaging materials (Evans, 2006).

- **Livestock Identification**

Laser technology is also being used in livestock management, providing a tamper-resistant and permanent method of identifying animals. Common methods include laser-engraved ear tags and skin markings, which help ensure animals can be tracked accurately throughout their lifespan (Ng, Leong, Hall, & Cole, 2005). In regions such as Kenya, these tags are being adopted for cattle identification, facilitating better disease control and cross-border tracking (Bank, 2018).

Marking for Packaging and Product Branding

In agricultural packaging, laser systems offer a reliable and flexible solution to add identifiers like barcodes, QR codes, or custom logos to materials such as wood, cardboard, and plastic (Ming et al., 2008; Ng et al., 2005). The technology helps reduce reliance on stickers and printed labels, thus contributing to environmental sustainability. In Nigeria, for instance, laser-engraved branding is being adopted to enhance product visibility and compliance in both local and export markets (Bank, 2018).

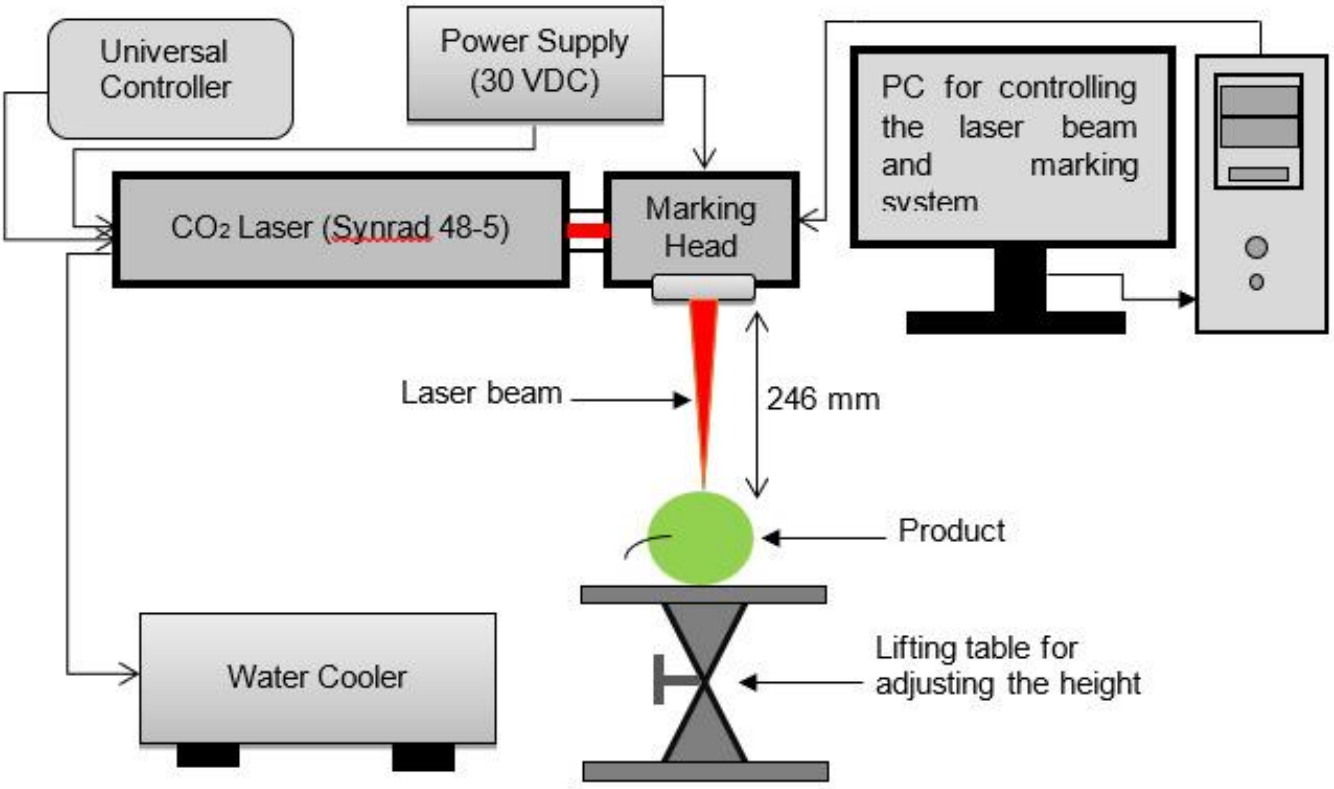


Figure 1. Laser marking experiment setup showing the CO_2 laser. CO_2 Laser: Synrad 48-5 (manufacturer: Synrad, model: 48-5), Power Supply: 30 VDC unit for laser operation. Marking Head: Not enough detail is provided in the image. For clarity, authors should include the manufacturer and model of the marking head in the manuscript. PC Controller: Used for software-based control of laser marking parameters. Universal Controller & Water Cooler: Supportive systems for laser operation and cooling. Product Positioning System: Lifting table, which requires manual height adjustment to position the product correctly.

Regulatory Compliance and Traceability

As global standards for food safety and traceability become more stringent, laser marking is increasingly being used to embed detailed product information such as harvest date, location, and certifications directly on the product or its packaging (Bruton, 1997). Kenyan exporters of tea use this method to meet international traceability demands and gain access to high-value markets (Chemeltorit, Gonzalez, & Gema, 2018; Ouma, 2010).

Economic and technical advantages of laser marking over paper labelling

Laser marking technology offers clear technical and economic benefits compared to traditional paper labelling. Technically, laser marking allows manufacturers to etch serial numbers, barcodes, logos, and batch details directly onto product surfaces with high accuracy and permanence (Han & Gubencu, 2008). Unlike paper labels, which are prone to tearing, fading, or peeling, laser markings are resistant to wear, chemicals, moisture, and extreme temperatures. This durability makes them especially suitable for sectors like electronics, automotive, pharmaceuticals, and food packaging, where traceability and product authenticity are crucial (Hoekstra et al., 2008; Shao et al., 2024). From a cost perspective, laser marking significantly lowers long-term operational expenses by eliminating the need for consumables like ink, paper, and adhesives. Although the initial investment in laser equipment is higher, maintenance costs are minimal, and there is no need for continuous material purchases (Stutz, 2016). In contrast, paper labelling involves recurring costs and often requires additional labour to apply and inspect labels, driving up production expenses over time. Laser systems also enhance production efficiency by supporting automation and in-line integration, thereby reducing reliance on manual labour (Shao et al., 2024).

Another advantage is that laser marking eliminates problems related to inventory management and label waste. Companies no longer need to stock various types or sizes of labels, simplifying logistics. Paper labels can also detach or be incorrectly applied, leading to issues like product recalls or damaged brand reputation. Additionally, laser systems can be easily reprogrammed to change markings without halting production, making them ideal for customised or small-batch manufacturing, which traditional labelling struggles to accommodate (Hoekstra et al., 2008). In summary, although paper labels may still be practical for low-budget or small-scale operations, laser marking stands out for its precision, durability, and long-term cost-efficiency. Its compatibility with modern Industry 4.0 environments further supports its role as a forward-looking solution for businesses aiming for scalability and reliability in product identification (Frankó et al., 2020).

Assessing the economic feasibility of laser marking versus other technologies

When it comes to economic feasibility, laser marking holds a competitive edge over other marking technologies like inkjet printing, thermal transfer printing, and dot peen marking. One key benefit of laser systems is their non-contact and wear-free operation, which translates to lower maintenance costs and minimal downtime (Hoekstra et al., 2018). In contrast, inkjet printers need regular cartridge replacements and nozzle maintenance, while thermal printers consume ribbons and have components that wear out quickly (Hack, 2003). Laser systems also offer faster processing times than dot peen systems, which are slower, especially when marking harder materials. While ink-based systems may be quicker in some scenarios, they involve ongoing costs for ink, solvents, and cleaning supplies and pose environmental risks. Laser marking, on the other hand, is clean, free of consumables, and environmentally sustainable (Han & Gubencu, 2008; Sobotova & Badida, 2017).

From a return on investment (ROI) standpoint, manufacturers, particularly those with high production volumes, often experience faster payback periods with laser systems because of their low running costs and high reliability. Moreover, a single laser machine can mark a variety of materials, including metals, plastics, glass, and ceramics, reducing the need for multiple systems. This versatility is especially valuable in highly regulated industries like aerospace, electronics, and medical devices, where permanent marking is required (Javale & Nair, 2013). Although the initial cost of acquiring a laser system can be high, options such as financing, depreciation benefits, and operational savings make the investment justifiable over time (Jutkowitz et al., 2010). As laser system prices fall and user-friendly software becomes more accessible, small and medium-sized enterprises (SMEs) are increasingly embracing the technology. Its scalability, efficiency, and adaptability make laser marking a smart long-term economic choice (Phillips et al., 2015).

Implementing laser marking in Africa and cost recovery after deployment

In the African context, successfully adopting laser marking requires investment in the right infrastructure and workforce training. The most relevant laser systems include fibre lasers (best for metals), CO_2 lasers (suited for materials like wood, plastic, and glass), and UV lasers (ideal for delicate surfaces) (Fofana et al., 2023). These systems must be paired with industrial cooling units, design and control software, automated conveyors for inline marking, and safety enclosures that meet international workplace standards. Countries with growing manufacturing sectors, such as Ghana, Nigeria, Kenya, and South Africa, are well-positioned to integrate laser technology in areas like agro-processing, pharmaceuticals, textiles, and automotive parts (Sanni et al., 2007). Thanks to increasing access to renewable energy and investments in industrial infrastructure, Africa is becoming more capable of supporting such high-tech systems. Government incentives such as tax breaks and import duty exemptions for technology are making laser equipment more accessible (Chidolue et al., 2024). While the purchase cost can range from $10,000 to $50,000 depending on the laser type, medium- to large-scale enterprises, especially those in the export market, can typically recoup this investment within two to three years due to enhanced compliance with international traceability and labelling standards (Klenam et al., 2025).

Africa's expanding participation in global value chains for products like cocoa, shea butter, textiles, and coffee makes the case for investing in high-quality, durable marking technologies even stronger (Ajibo, 2023). The African Continental Free Trade Area (AfCFTA) further encourages local businesses to adopt modern technologies that boost cross-border competitiveness. Laser marking not only ensures compliance but also builds customer confidence by reinforcing product reliability and brand integrity (Ajibo, 2023). To achieve full cost recovery, businesses need to invest in operator training, regular maintenance, and seamless integration of laser systems into existing production workflows. Supportive government policies and collaborative public-private partnerships can further accelerate adoption and knowledge sharing (Lall, 2004). With the right strategies in place, African manufacturers can leverage laser marking technologies to enhance efficiency, meet international standards, and increase their global market competitiveness (Lall, 2004).

Benefits of Laser Marking for African Agriculture

Laser marking technology offers a forward-thinking approach that can significantly contribute to improving productivity, sustainability, and global competitiveness in African agriculture. Its benefits span traceability enhancement, packaging waste reduction, brand visibility, and streamlined operations.

Strengthening Traceability and Monitoring

Ensuring that agricultural goods can be tracked reliably from production to consumption is a cornerstone of modern food systems. Laser marking enables the application of permanent and detailed identifiers such as barcodes or QR codes directly onto a product or its packaging (Bruton, 1997). These markings facilitate real-time monitoring throughout the supply chain, which is crucial in swiftly managing food safety concerns and product recalls. Moreover, enhanced traceability supports compliance with international food safety protocols, positioning African agricultural producers to access and thrive in foreign markets (Dandage, Badia-Melis, & Ruiz-García, 2017; Jaffee, Henson, Unnevehr, Grace, & Cassou, 2018).

Minimizing Packaging Waste

Sustainability has become an essential consideration in agricultural practices globally. One significant advantage of laser marking is its contribution to reducing dependency on non-essential packaging elements (Dewees & Hare, 1998; Ma et al., 2019; Raney, Hogan, McCollom, & Meyer, 1994). By inscribing essential information directly onto products or their primary packaging, producers can limit the need for materials such as plastic labels or paper tags (Petljak, Naletina, & Bilogrević, 2019; Raheem, 2016). This not only lowers environmental impact but also reduces costs and aligns with the preferences of environmentally aware consumers (Sobotova & Badida, 2017).

Enhancing Brand Identity and Customer Confidence

Laser technology allows for detailed, customizable inscriptions including brand logos, certifications, or marketing messages on agricultural goods. These high-quality marks improve product presentation and visibility, which helps in building a strong brand presence in competitive marketplaces (Bruton, 1997). Furthermore, the transparency and traceability afforded by laser marking can bolster consumer trust, as customers are increasingly seeking detailed information about the origin and handling of their food (Odintsova et al., 2019; A. Zhang, Mankad, & Ariyawardana, 2020).

Boosting Operational Productivity

Integrating laser marking into agricultural operations can drive substantial efficiency gains. These systems operate at high speeds and are easily automated, significantly cutting down production delays (Yu, Wang, & Yu, 2012). Unlike traditional labelling methods, laser marking requires no consumables such as ink or labels, reducing ongoing operational costs. Additionally, the durability and precision of laser marks ensure that information remains legible throughout the supply chain, reducing errors and the need for rework (L. Wang et al., 2021).

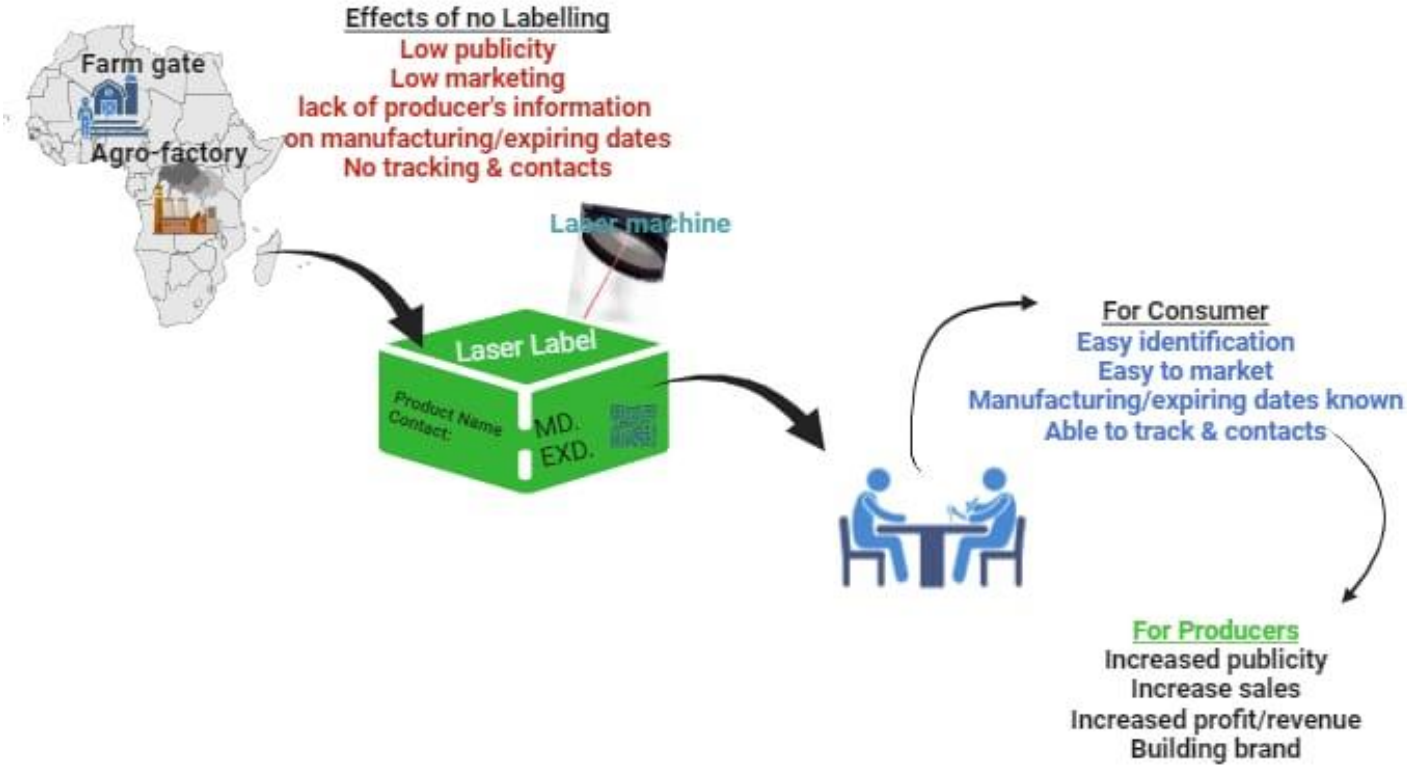


Figure 2. The application of laser marking in Africa.

Challenges and Limitations of Laser Marking in African Agriculture

Although laser marking holds promise for transforming agricultural practices in Africa, its rollout is met with several practical hurdles. These include environmental constraints, the steep cost of entry, a shortage of trained personnel, and reluctance from stakeholders to embrace new technologies.

- **Technological Barriers and Maintenance Needs**

Laser marking devices often struggle in typical agricultural settings across Africa, where harsh conditions like dust, fluctuating temperatures, and high humidity can compromise their performance (Tohidyan Far & Rezaei-Moghaddam, 2020). These factors not only affect the precision of the markings but also demand regular upkeep. In many rural or resource-limited areas, access to technical support and spare components is limited, complicating maintenance efforts (L. Wang et al., 2021). Building local repair networks and investing in rugged equipment designed for agricultural use is therefore essential.

- **Upfront Financial Investment**

The high purchase and installation costs of laser marking systems present a major barrier to adoption. Most smallholder farmers who make up a significant portion of Africa's agricultural workforce cannot afford such technologies without assistance (Flood, 2001; Oyelaran-Oyeyinka & Adeya, 2004). This situation underscores the importance of financial interventions, such as tailored loan packages, subsidies, and grant schemes, to make the technology more accessible (Soriano & Peris-Ortiz, 2011).

- **Need for Skilled Labour**

Operating and maintaining laser marking equipment requires specialized knowledge. Unfortunately, many regions lack the necessary training infrastructure or skilled labour to support the deployment of these systems (Hoffman, 1992; Mills, Grant-Jacob, & Zervas, 2023). Addressing this gap involves creating training programs and technical support hubs to ensure effective usage (Muqit, Aldington, & Scanlon, 2019).

- **User Acceptance and Trust**

Introducing advanced technologies in traditional sectors like agriculture often encounters scepticism. Many producers question the value and return on investment of laser marking systems. This reluctance can be mitigated through targeted outreach, live demonstrations, and highlighting how the technology enhances productivity and access to premium markets (Aryal, Rahut, Jat, Maharjan, & Erenstein, 2018; Lybbert, Magnan, Spielman, Bhargava, & Gulati, 2013).

Policy and Regulatory Environment for Laser Marking in African Agriculture

The smooth integration of laser marking into agricultural systems in Africa heavily depends on a supportive policy framework and an adaptive regulatory environment (Chigunta, Herbert, Johnson, & Mkandawire, 2004; Falck-Zepeda & Zambrano, 2013). Policies must not only foster adoption but also ensure the technology is used safely and responsibly.

Existing Supportive Policies

Several African nations have developed policies that encourage the use of technology to boost agricultural efficiency. For instance, the Comprehensive Africa Agriculture Development Programme (CAADP), promoted by the African Union, emphasizes innovation as a driver of agricultural growth (Henri-Ukoha, Osuji, Anyanwu, Okwara, & Eze, 2019). Countries such as Kenya, South Africa, and Nigeria have embedded technology adoption in their national agricultural strategies, opening doors for systems like laser marking to improve product traceability and quality (Bank, 2018).

Gaps in Regulation and Enforcement

Despite policy interest, regulatory systems often lag behind the pace of technological change. For laser marking, particularly when applied to food products, ensuring compliance with food safety norms is crucial. Furthermore, environmental issues such as the proper disposal of outdated equipment need to be addressed (Henri-Ukoha et al., 2019). Regulatory bodies must update their guidelines to incorporate safety and sustainability in the use of laser-based systems (Nadimi et al., 2021)

Policy Recommendations

To support widespread and responsible use of laser marking in agriculture, the following actions are proposed:

- Update Regulatory Frameworks: Introduce clear guidelines that prioritize consumer protection, environmental sustainability, and food safety (Weiner, 1990).
- Enhance Financial Access: Provide financial instruments like low-interest loans and grants to make the technology affordable for small-scale producers (Kafaji, 2019; Oluwamayokun, Rajendra, & Ammar, 2022).
- Build Local Capacity: Invest in technical training and infrastructure to ensure the long-term sustainability of the technology (Maqsood & Khalil, 2013).
- Promote Public-Private Synergies: Encourage collaboration between governments, private sector players, and research institutions to drive innovation (Hartwich et al., 2008).
- Track and Assess Outcomes: Create evaluation frameworks to measure how the technology affects agricultural value chains, guiding future policy revisions (Tohidyan Far & Rezaei-Moghaddam, 2020).

Future Prospects and Innovations in Laser Marking for African Agriculture

The potential of laser marking in Africa's agricultural future is vast, particularly as the technology evolves and becomes increasingly compatible with digital agriculture.

Next-Gen Laser Technologies

Ongoing innovations are improving laser marking's affordability and performance. The emergence of compact and energy-efficient fibre lasers is particularly promising (Hanna, 1993; PINTO & MACLEAN, 2010). Additionally, advancements in cold marking techniques where heat is minimized allow the safe use of delicate produce (Amuda & Akinlabi, 2016).

IoT and AI Synergy for Smart Agriculture

Laser-engraved IDs can be integrated with IoT devices to create a connected ecosystem for agriculture. This setup enables real-time monitoring and traceability across supply chains (Elijah, Rahman, Orikumhi, Leow, & Hindia, 2018). Coupled with AI, such systems can generate insights into market dynamics, predict trends, and optimize logistics (Sanchez-Jimenez & Salais-Fierro, 2021; Xie et al., 2019).

Key Areas for Further Research

Future studies should focus on material-laser interaction to tailor marking techniques for different agricultural products. There's also a need to evaluate the ecological footprint of laser systems, seeking energy-efficient solutions. Economic feasibility studies can help determine cost-benefit scenarios, while user-centered designs including local languages and symbols can drive broader acceptance.

Recommendation for Laser Marking Technology in Ghana

Ghana's poultry sector is a vital source of food, particularly eggs, which are widely consumed across the country. Yet, these eggs typically reach consumers without any traceable information such as the laying date, farm of origin, or chicken breed. Introducing laser marking technology in this context could significantly improve transparency and consumer confidence.
Given the demonstrated environmental and informational benefits of egg marking technologies in regions like Europe, Australia, and North America, similar adoption in Ghana could modernize the sector. Labelling eggs with laser-etched data can provide essential information to consumers, streamline supply chains, and support regulatory oversight all without using inks or packaging. Considering its potential to uplift both food safety and market appeal, laser marking represents a forward-thinking investment for Ghana’s agricultural future.

Table 1. State of the art of laser parameters and application on agricultural/biological products.

Product	Laser Energy (mJ or J)	Laser Power (W)	Barcode Size (mm)	Notes	References
Lemon	150–400 mJ per pulse	10–30 W	10 × 10 to 20 × 20 mm	Shallow etching to avoid deep burns	(G Drouillard & Rowland, 1997; Etxeberria et al., 2009)
Orange	150–350 mJ per pulse	10–30 W	10 × 10 to 25 × 25 mm	Similar to lemon, softer skin	(Danyluk, Villeda, Friedrich, Schneider, & Etxeberria, 2010; Heck, Ibarra, & Sheffler, 2007)
Citrus fruits (general)	150–400 mJ per pulse	10–40 W	10 × 10 to 20 × 20 mm	Grapefruit needs slightly higher energy	(G Drouillard & Rowland, 1997; Liu et al., 2019)
Green Pepper	80–150 mJ per pulse	5–15 W	8 × 8 to 15 × 15 mm	Fragile skin, lower power preferred	(Greg Drouillard & Kanner, 1999; G Drouillard & Rowland, 1997)
Apple	100–300 mJ per pulse	5–25 W	12 × 12 to 20 × 20 mm	Waxy layer requires careful tuning	(Eyahanyo & Rath, 2020; Hoult, 2017; Longobardi, 2007; Ma et al., 2019)
Peach	80–150 mJ per pulse	5–15 W	8 × 8 to 12 × 12 mm	Soft skin; low energy marking	(Greg Drouillard & Kanner, 1999)
Tomato	50–120 mJ per pulse	5–10 W	6 × 6 to 12 × 12 mm	Very delicate; minimum energy used	(Etxeberria et al., 2006; Yuk, Warren, & Schneider, 2007)
Onion	150–300 mJ per pulse	10–20 W	10 × 10 to 15 × 15 mm	Dry skin allows higher energy	(Greg Drouillard & Kanner, 1999)
Plum	80–150 mJ per pulse	5–10 W	8 × 8 to 12 × 12 mm	Soft like peaches	(Greg Drouillard & Kanner, 1999)
Kiwi	100–250 mJ per pulse	8–15 W	8 × 8 to 15 × 15 mm	Thin skin	(Greg Drouillard & Kanner, 1999)
Pears	120–300 mJ per pulse	10–20 W	10 × 10 to 20 × 20 mm	Similar behavior as apples	(Barcikowski, Koch, & Odermatt, 2006)
Avocado	150–400 mJ per pulse	10–30 W	15 × 15 to 25 × 25 mm	Harder, oily surface	(Etxeberria et al., 2006; White, 2008)

Potatoes	200–500 mJ per pulse	20–50 W	10 × 10 to 20 × 20 mm	Thick skin	(Etxeberria et al., 2006)
Eggs	50–200 mJ per pulse	5–15 W	6 × 6 to 10 × 10 mm	Very fragile surface, shallow	(Danyluk et al., 2010; Etxeberria et al., 2006; Griffiths & Fox, 2011; Parker, 2011)
Cucumber	80–200 mJ per pulse	8–15 W	10 × 10 to 20 × 20 mm	Sensitive to heat	(Etxeberria et al., 2006)
Grapefruit	200–500 mJ per pulse	20–50 W	15 × 15 to 25 × 25 mm	Thick, robust skin	(Sood, Exteberria, Narciso, & Ference, 2009; Sood, Ference, Narciso, & Etxeberria, 2008, 2009)
Cavendish Banana	100–250 mJ per pulse	8–20 W	10 × 10 – 20 × 20 mm	Delicate peel; soft marking needed	(Nasution & Rath, 2017)
Citrus Leaves	20–80 mJ per pulse	2–10 W	5 × 5 to 8 × 8 mm	Very fragile, non-invasive marking; used mainly to assist chemical uptake	eberria & Gonzalez, 2014; ria, Gonzalez, Fanton Borges, & en, 2016)
Coconut	300–700 mJ per pulse	30–50 W	15 × 15 to 30 × 30 mm	Hard, thick shell requires high energy for visible marking	(Zighelboim, 2015)

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