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REVIEW

ADOPTION OF SMART AGRICULTURE IN COCOA PRIMARY PROCESSING

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ABSTRACT – *Currently, the Malaysian cocoa industry is focusing on the production of fine flavour cocoa beans. The production of fine flavour cocoa beans is greatly influenced by various factors including primary processing which consists of several steps namely harvesting, fermentation and drying, to transform fresh cocoa beans into dried cocoa beans. Although smallholders have been trained thoroughly in cocoa primary processing, the quality of cocoa beans produced is still inconsistent. Therefore, this paper explores the potential of adopting smart agriculture in cocoa primary processing to ensure consistent and premium cocoa beans quality. The discussion will highlights the utilization of sensors during harvesting to classify cocoa pods according to their internal health and maturity levels, aiming to mitigate the risk of losses caused by pest and disease damage as well as the presence of under or overripe pod. Finally, the discussion will extend to the use of sensors to monitor parameters like temperature, colour, pH, microbes and moisture levels during processing. This monitoring will allow smallholders to adjust the processing conditions promptly to ensure optimal fermentation and drying which are critical conditions for consistent production of high-quality dried cocoa beans.*

Keywords: Smart agriculture, cocoa quality, harvesting, fermentation, drying

INTRODUCTION

Agricommodity refers to agriculture-based commodities and is one of the important components of the Malaysian economy. Among the eight commodities prioritised within the National Agricommodity Policy 2021-2030 (DAKN2030), cocoa is the fourth largest Agricommodity following oil palm, rubber, and timber (MPIC, 2021). In 2023, the export value of cocoa beans and products reached RM8.21 billion, compared to the previous year's RM7.82 billion (MCB, 2024a). Although the contribution to Gross Domestic Product (GDP) increased, the income of cocoa smallholders remains low. Whereby, the average net income for cocoa smallholders is estimated at RM 519 per month for bulk beans (MCB, 2024b). This earning falls significantly below Malaysia's minimum wage and poverty line income, which are RM1,500 per month (Malaysian Bureau of Labour Statistics, 2022) and RM2,589 per month, respectively (DOSM, 2023). Malaysian cocoa planting is predominantly cultivated by 5,452 smallholders, covering 88.93% of the total 6,123.07 hectares of cocoa plantation area recorded in the year 2023 (MCB, 2024a). Hence, enhancing the income of the key players in cocoa planting has become a priority for the Malaysia Cocoa Board (MCB, 2022).

Nowadays, dried cocoa beans are classified into two categories namely bulk and fine flavour. Bulk cocoa refers to dried cocoa beans with ordinary flavour quality that can be easily obtained from multiple sources of global cocoa farms and is usually used in the mass production of semi-finished products such as cocoa liquor, cocoa butter, and cocoa powder (Anon, 2023; Castro-Alayo *et al*., 2019). Whereas the fine flavour cocoa (FFC) is dried cocoa beans with a unique flavour such as flowery, fruity, caramelly and nutty, which is difficult to obtain and usually can be differentiated by region (Quelal-Vásconez *et al.*, 2020). Due to their unique flavour quality, price offers for the FFC are very high, starting at around 20% and sometimes reaching double or triple the price of bulk cocoa beans (Beckett *et al*., 2017). Production of the bulk quality cocoa beans has been identified as one of the factors contributing to the lower income earned by the Malaysian cocoa smallholder. Therefore, the Malaysian cocoa industry is strategically shifting its focus toward production of the FFC beans, thereby addressing the low earning issue of the smallholders (MCB, 2022).

Cocoa beans that are directly dried after being extracted from the pod will lack of chocolate aroma or flavour and exhibit an extreme taste of astringency and bitterness (Khairul Bariah, 2018). Fresh cocoa beans must undergo primary processing, also known as post-harvest processing before they are transformed into dried cocoa beans with the desired chocolate flavour (Fowler and Coutel 2017). The process holds significant importance because poor handling results in the production of the dried beans with subpar flavour quality (Zanuri *et al*., 2021). The Malaysian Cocoa Board has provided a detailed standard of operation (SOP), emphasizing control over cocoa primary processing, to achieve optimal processing and ensure the desired flavour and colour of dried beans produced. Through this approach, several Malaysian cocoa smallholders have successfully gained recognition for producing of the FFC beans. However, despite face-to-face training on these guidelines, the Malaysian cocoa industry still faces challenges, and the number of recognized smallholders remains low. To address these drawbacks, exploring the adoption of smart agriculture technologies in cocoa primary processing is essential to ensure consistent production of the FFC beans. Detailed information on conventional primary processing will be discussed to understand the potential adoption of smart agriculture technology in primary processing. This review aims to serve as a valuable resource, offering insights for researchers in the cocoa industry.

COCOA PRIMARY PROCESSING

Cocoa primary processing is carried out on the farm and encompasses several intricate stages, as illustrated in Figure 1. Over the years, researchers have declared that fermentation is the most crucial process in determining the flavour quality of cocoa beans (Guzmán-Alvarez and Márquez-Ramos, 2021; Fowler and Coutel, 2017). However, in reality, each of the processing stages, including harvesting and drying, holds equal importance, where poor handling at any processing stage will result in the production of dried cocoa beans with subpar flavour quality (Forte *et al*., 2022; Zanuri *et al*., 2021, Santander *et al*., 2021; Santander Muñoz *et al*., 2019). Recent findings by Villacis *et al*., (2021) revealed that the final quality of commercial cocoa beans is influenced by agronomic practices, environmental conditions, fermentation and drying irrespective of the type of variety grown, ultimately determining their price.

Harvesting

The cocoa fruit, also known as pod, develops in clusters from pollinated flowers which arise directly on the auxiliary bud of main stem as well as branches of the tree. The pod will takes approximately 120 to 180 days (four to six months) from pollination to ripen depending on the variety and may differ in terms of size, shape, and colour (Aizat *et al*., 2020; Cierjacks, 2020). Ripe cocoa pods will not fall off, they remain on the tree until harvested by manually cutting from the tree either using machetes or secateurs (Figure 2). Conventionally, Malaysian smallholders will visually inspect the cocoa pod husk with the unaided eye for the colour changes on the surface of cocoa pod husk. Whereby, the pod husk colour can generally be either green, red or maroon when immature and will change to yellow, orange or red upon ripening (Figure 3). In some varieties, mature pods are difficult to identify because there are almost no noticeable changes in colour or shape (Cierjacks, 2020). In this case, experienced smallholders determine the ripe cocoa by tapping the pod and evaluating the difference in the sound produced (Baculio and Barbosa, 2022).

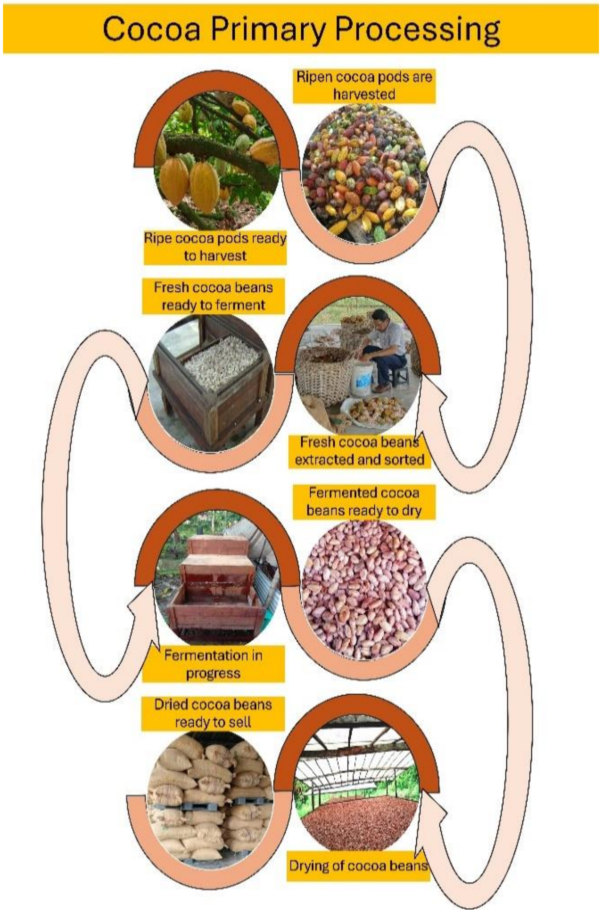

Figure 1: A flow of conventional cocoa primary processing.

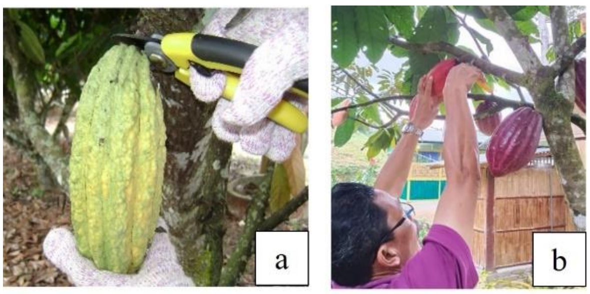

Figure 2: Harvesting ripe cocoa pods by cutting on the stalk close to the cocoa pod (a) yellow pod (b) red.

Cocoa pods should be harvested at the ideal ripening stage, as their maturity level greatly affects the quality of the resulting beans (Tee *et al*., 2022; Cubillos Bojacá *et al*., 2019). However, smallholders tend to pick unripe compared to overripe pods, as they would harvest as early as possible to avoid crop loss to pests. The unripe pods are reported to have insufficient content of storage proteins, fats, and sugars as these compounds fully accumulate within the last three weeks before ripening. Whereas protease and peptidase enzymes are synthesized at a later phase (Rawel *et al* 2019; Mustiga *et al*., 2019; Rohsius *et al*., 2010). These compounds are essential as sources of flavour precursors during fermentation and flavour formation during another processing stage. On the other hand, overripe pods have slightly dried beans, which may start to germinate inside the fruit and lead to an increased percentage of cocoa waste during grading. Additionally, cocoa pod borer (CPB) infestation on immature cocoa pods adds to the difficulty of smallholders detecting the level of maturity and health status of the pods (Meilin *et al*., 2024).

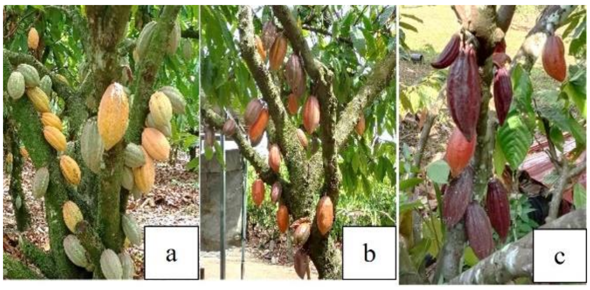

Figure 3: Cocoa pods colour from immature to mature (a) green to yellow (b) red to orange (c) marron to red.

After being harvested, the pods should be split open. Fresh cocoa beans are removed and sorted from placenta or husk fragments as a preparation for the next process, which is fermentation. Usually, Malaysian smallholders carry out the preparation either at the farm or near the location where fermentation will take place. The commonest practice for pod breaking is by manually hitting them together or using a machete. Upon completing the sorting, the fresh cocoa beans will be placed into a container depending on which fermentation techniques will be practiced and ready to ferment.

Fermentation

Fermentation is identified as one of the crucial processes in producing dried cocoa beans with the desired flavour (Pokharel, 2023; Calvo *et al*., 2021). There are various fermentation techniques, and it solely depends on the smallholders to apply which technique. In Malaysia, cocoa smallholders are recommended to use shallow box fermentation as a study by Papalexandratou *et al*., (2013), revealed that cocoa beans obtained from spontaneous fermentation using shallow box managed to produce high-quality chocolate. The process commences by placing the sorted fresh cocoa beans (later known as fermenting mass) into the box which comes with sufficient perforation for effective drainage during sweating. Based on previous research, the fermentation process requires a sufficient depth of fermenting mass of about 30 cm to guarantee that adequate heat is produced during the process. In the case of insufficient cocoa beans, the shallow box wall can be adjusted to ensure that the height of the fermenting mass remains consistent (Figure 4). The fermenting mass needs to be covered appropriately either with a clean gunny sack or plywood to prevent heat from escaping into the surrounding environment (Figure 5). In addition, the fermenting mass should be turned by transferring the fermented beans mass from one box to another at least once throughout the fermentation process to allow good aeration and ensure the beans are mixed uniformly. It is suggested that the wet cocoa beans should be mixed when they appear relatively dry, separated from each other, and have a very thin pulp layer, as well as about 30% of them, having marron-purple spots (Figure 6).

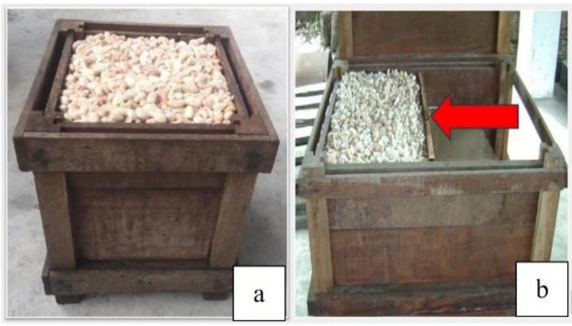

Figure 4: Fresh cocoa beans (a) sufficient (b) insufficient are loaded into a shallow box.

Figure 5: Fermentation in the shallow boxes (a) cover with gunny sacks and (b) cover with plywood.

Figure 6: The cocoa beans appearance before mix. Arrow shows the marron-purple spot.

During fermentation, various chemical reactions occur and can be divided into two phases, namely pulp (outside) and cotyledon (inside) fermentation. The pulp fermentation, also known as external fermentation, begins as soon as the cocoa seeds are exposed to the environment. This phase is attributable to the metabolism of an ordered microbial succession of a wide range of yeasts, lactic acid and acetic acid bacteria, some aerobic spore-forming bacteria and various species of filamentous fungi producing metabolites such as ethanol, lactic acid, acetic acids and heat (Hirko *et al*., 2023; Guzmán-Alvarez and Márquez-Ramos 2021; Santander Muñoz *et al*., 2020; De Vuyst and Weckx, 2016). The resulting heat is sufficient to increase mass temperature above from ambient temperature.

On the other hand, the otyledon fermentation involves enzymatic reactions that occur inside the cocoa beans. The phase starts with the diffusion of ethanol into the micropyle, altering the cellular structure and resulting in the testa's loss of selective permeability as well as the membrane barrier no longer functioning. Consequently, it enables the diffusion of acetic acid into the cotyledons, or a process known as nib acidification, allowing other biological components such as enzymes inside the cotyledons (e.g. invertase, endoprotease, glycosidase, and polyphenol oxidase) and their substrates (e.g. anthocyanins, flavanols, phenols, carbohydrates and storage proteins) freely mixing. In response to nib acidification and sufficient heat in fermenting mass, the cocoa enzymes are activated and react with major molecules such as storage proteins, polysaccharides, fat and polyphenols to produce aroma and flavor precursors (Pokharel, 2023; Calvo *et al*., 2021; Khairul Bariah 2018).

Drying

Drying is a process to reduce the moisture content of the wet fermented cocoa beans from 20-30% to only 7-7.5% (Niikoi Kotey *et al*., 2022; Ackah and Dompey, 2021). Reducing the moisture content will prevent the growth of molds and ensure a good storage condition for dried cocoa beans. Low moisture content can also inhibit excessive proteolysis by deactivating the endogenous enzymes, thus preventing the production of over-fermented or off-flavour beans. Besides reducing moisture, drying also ensures that the reddish-brown colour of cocoa beans is transformed to fully brown (Niikoi Kotey *et al*., 2022; Dzelagha *et al*., 2020). The drying process should be carried out as soon as optimal reaction of the fermentation process is achieved. To date, there is disagreement over when the correct duration of the fermentation process termination. Usually, the process is terminated based on the smallholders' experience (Hirko *et al*., 2023; Guzmán-Alvarez and Márquez-Ramos 2021;). Whereby, the optimal reaction of the fermentation process is manifested by decreasing the fermenting mass temperature and increasing intensity of the vinegar or acetic acid odour. Additionally, it has been suggested that the fermentation process which is carried out under optimal conditions should not be longer than four days. Otherwise, undesirable bacilli and filament fungi that co-exist with beneficial microbiology during the initial phase may interfere with the fermentation process and will negatively impact the quality of the dried cocoa beans (Hirko *et al*., 2023; De Vuyst and Weckx 2016).

Apart from the above-mentioned, Malaysian cocoa smallholders are trained to determine the optimal fermentation process based on the appearance of the cocoa beans. Whereby, the cocoa beans are slightly dried, separated from each other, blotted and reddish in colour as well as almost all of them, have marron-purple spots on them (Figure 7). Most of the smallholders performed the drying process using sun-drying on the raised platform under transparent shading. The cocoa beans are spread out in thin layers on the drying platform for five to ten days, depending on the location and climate (Figure 8). Additionally, the cocoa beans also need to be turned every two to three hours periodically, particularly on the first day to ensure all the beans are heated equally and prevent blackish beans due to the ongoing fermentation process. Some smallholders use artificial dryers during the rainy season, where the heating sources are liquid petroleum gas (LPG), firewood, and diesel. The smallholders using artificial dryers are advised to control the drying temperature below 60°C and avoid direct drying (Dzelagha *et al*., 2020; Kelvin *et al*., 2013). Upon drying, a handful of the beans is grabbed and rubbed against each other to determine whether the beans have been dried adequately. If a crackling sound is produced, the cocoa beans are sufficiently dried (Kelvin *et al*., 2013).

Figure 7: The cocoa beans appearance when fermentation should be ended. Arrow shows the marron-purple spot.

Figure 8: Cocoa beans are spread in thin layers.

SMART AGRICULTURAL IN COCOA PRIMARY PROCESSING

Smart agriculture, also known as smart farming, digital farming or agriculture 4.0, is a cutting-edge technology aimed at improving the efficiency, productivity, and quality of the agricultural industry (Osrof *et al.*, 2023). According to Aceto *et al*., (2019), smart agriculture has ten digital-based technology enablers including the following: Big Data, Internet of Things, Cloud Computing, Fog and Mobile Computing, Artificial Intelligence, Human-Computer Interaction, Robotics, Open-Source Software, Blockchain, and the Internet, which are strongly interrelated. Trivedi and Nandeha, (2020) have described smart agriculture as the integration of information and communication technologies into agricultural machinery, equipment, and sensors, enables the generation of a large volume of data and information while gradually incorporating automation into the process. The subset of technology under smart agriculture is very wider and ever-expanding (Garg and Alam 2023; Sing *et al.,* 2022). Thus, this paper only focuses on the potential use of sensors during harvesting, fermentation and drying with the aim that cocoa primary processing will be in the optimal condition and able to produce high quality dried beans consistently.

Identifying which amongst the pods are ripe enough, free from pests and diseases and ready for the next stage of the cacao process is the beginning of the production of high quality dried cocoa beans. Studies focusing on the use of sensors for such identification in Malaysia have already started since 2017 or even earlier. Whereby, Tee *et al*., 2018 have explored the use of a multiparametric fluorescence sensor to determine the optimum harvest time of cocoa pods by estimating anthocyanin, flavonol, chlorophyll and nitrogen balance. They found out that cocoa pods are commercially ready to harvest when they reach month 4 after pod emergence as the beans have developed a good quality dried beans and comply with the Malaysian standard on cacao bean specification. In 2019, the effectiveness of laser-induced backscattering imaging (LLBI) in determining the firmness and colour of cocoa pods at different maturity stages has been investigated by Lockman *et al*., Their study demonstrated that the non-destructive LLBI with laser diode emitted light at 705 nm wavelength able to evaluate the maturity stages of cocoa pods.

In addition, researchers from Philippines also studied the potential usage of sensor on cocoa pods maturity. Arenga *et al*., (2017) has proposed classification of cocoa pods ripeness by using acoustic sensing device. The device acquired a acoustic data from cocoa pods which classified as ripe and unripe while still on tree. By using Fast Fourier Transform (FFT) to extract spectral characteristics and Support Vector Machine (SVM) as classifier tool, the technique is managed to correctly classify cocoa ripeness with 95.8% overall accuracy. Whereas a technique to determine the ripeness of cacao through spectrogram and convolutional neural network (CNN) has been developed by Bueno *et al*., (2020). The technique that used application of tapping on the cocoa pods for sound data has successfully classified whether the cocoa is unripe or ripe with 97.46 % accuracy mean of the classification system. However, no data on the quality of the resulting dried cocoa beans are provided either by Lockman *et al*., (2019), Arenga *et al*., (2017) or Bueno *et al*., (2020).

Research on the use of sensors during cocoa fermentation to determine whether cocoa fermentation occurs optimally or not primarily focuses on temperature. Paez *et al*., (2020) have studied the usage of temperature sensors that can be operated in a finite porous media in the fermentation box with dimensions of 100 cm × 90 cm × 80 cm. While a real-time monitoring system for cocoa fermenters is developed by Tovar Perilla, (2022). The researcher used digital temperature sensors and humidity-temperature sensors to monitor the environmental conditions during the fermentation process. On the other hand, Lazarte Rivera *et al.*, (2018) have designed cocoa fermenter from wood equipped with temperature and pH sensors as well as an electrical motor as the actuator. The fermenter concept almost resembles a prototype that had been developed by previous researchers from

MARDI. However, this fermenter is more advanced with sensors.

Tan *et al*., (2019) studied electronic nose (e Nose) system using six machine-learning methods namely: bootstrap forest, boosted tree, decision tree, artificial neural network (ANN), naïve Bayes and k-nearest neighbors to classify the fermentation duration of cocoa beans in a polystyrene box. They discovered that the bootstrap forest algorithm had a misclassification rate as low as 9.4%, while ANN and boosted tree had misclassification rates of approximately 12.8 and 13.6%, respectively. Other machine learning based failed to perform classification for cocoa beans.

Research on the use of sensor technology during cocoa drying is still limited. Existing studies are mainly focused on evaluating the quality of the dried cocoa beans produced. Among the researchers who utilize the E-Nose sensor system are Nazli *et al*., (2021), Scavarda *et al*., (2021), Florez *et al*., (2020), and Hidayat *et al*., (2019). In contrast, Kutsanedzie *et al*., (2017) employed near-infrared chemodyes systems. Interestingly, Almeida *et al.*, (2020) is the only group proposing the use of biological sensors based on cell-to-cell communication to evaluate and classify dried cocoa beans.

CONLUCIONS

Consistent quality of dried cocoa beans is essential for cocoa smallholders' income and ensuring their well-being. Production of high-quality dried cocoa beans depends on proper cocoa primary processing. Whereby, the optimal conditions of cocoa primary processing are obtained from the use of ideally ripe cocoa pods with free pests and diseases, an optimal fermentation process as well as drying adequately. However, all the important parameters are mostly monitored using human judgment, which is subjective. Therefore, adopting sensor based smart agriculture in cocoa primary processing will ensure consistent and premium cocoa beans quality produced.

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