A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach

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**ABSTRACT**

Palm oil is a renewable resource that has the potential to replace fossil fuel and petrochemical for a better sustainable system. However, there is room for improvement in the current operation of the palm oil industry to achieve better sustainability development. The industrial revolution toward automation and artificial intelligence (AI) is the new trend known as the fourth industrial revolution (Industry 4.0). Unfortunately, the palm oil industry has been moving slowly in this revolution. This paper aims to conduct a detailed review of the current state of the palm oil industry development toward Industry 4.0. A novel Hazard and Operability Analysis (HAZOP) approach is adopted i) to ensure a detailed evaluation of the existing problems, and ii) to identify potential implementation of Industry 4.0 technologies in the palm oil industry. HAZOP is a common approach used in chemical engineering to systematically evaluate process safety and identify the possible improvement of the existing system. The same concept is applied in this paper to investigate the possible adaptation of Industry 4.0 technologies to improve the palm oil industry. Existing Industry 4.0 technologies and features were evaluated to identify feasible adaptation in the industry. The HAZOP review proposed 23 recommendations to improve the palm oil industry with Industry 4.0 technologies to achieve a higher standard in sustainable production. A total of 13 specific Industry 4.0 features were identified as the potential development gaps for palm oil industry stakeholders, which included the adaptation of Internet-of-Things sensors, cloud computing, blockchain, and smart imaging processing technologies.

**1. Introduction**

The rapid development of industrialisation to improve the quality of life, especially to meet the increasing demand of energy consumption has significantly increased pollution. Recent developments focus on reducing the dependence on fossil fuel by replacing it with other environmentally-friendly and renewable resources such as solar, wind and geothermal. Significant research has been conducted to improve renewable energy production to achieve the sustainable goal initiated by the European Union to reduce 20% of the carbon dioxide and energy consumption by 2020 [1]. Being one of the primary sources for edible oil, chemical product and energy, palm oil industry has been growing rapidly due to the increasing demand. Global palm oil production increases tremendously in the past decades, almost doubling every 10 years [2]. Reported global industry consumption of palm oil and palm kernel oil was about 19.72 million tons in 2018, while the highest producing country, Indonesia, alone aims to produce 40 million tons by 2020 [3,4]. A study shows that palm oil is an energy crop which has the highest oil production yield as compared to other oil crops [5]. This enables optimum usage of limited plantation site (or land) to generate the highest amount of oil for food, chemical and energy applications. Apart from that, wastes generated from palm oil industry such as palm biomass and palm oil mill effluent have shown to be a promising

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alternative for renewable energy generation. For example, palm biomass can be used in pyrolysis, gasification, combustion, and liquefaction process to generate energy [6].

Despite being a promising renewable resource, a study shows that the palm oil industry has caused adverse environmental impacts, such as deforestation, habitat loss, pollution (water and air) and forest fire [2]. With the constant international pressure and heightening demand for sustainable palm oil production, the Roundtable on Sustainable Palm Oil (RSPO) standard was established to promote the production of Certified Sustainable Palm Oil (CSPO) for environment protection [7]. Being the major palm oil producers, Malaysia and Indonesia have initiated Malaysia Sustainable Palm Oil (MSPO) and Indonesia Sustainable Palm Oil (ISPO) schemes respectively. However, regardless of numerous efforts and awareness campaigns to promote MSPO and ISPO, the adaptation of CSPO production was slow, especially among small and medium enterprises (SMEs). Researchers highlighted several reasons for CSPO implementation failure, including premium for the CSPO is too low compared to the implementation cost, as well as the complex system to trace and differentiate CSPO and non-certified palm oil [8]. Another study suggested that certified palm oil production is not as sustainable as it claimed as the certification process might cause more tree losses [9].

Numerous efforts have been contributed by researchers to improve the RSPO system from different aspects. For example, RSPO evaluation method was discussed and enhanced with a new and improved quantitative assessment tool based on air, water, and soil criteria [10]. Alternative standard schemes for sustainable palm oil were evaluated to suggest that the future development of the industry should be focusing on increasing participation of smallholders in CSPO certification [11]. Apart from the efforts to achieve certified production, other researchers have contributed to improve sustainability practice in oil palm technologies. Multi-objective optimisation model that incorporated stakeholders’ and experts’ value judgement was proposed to improve the planning of sustainable oil palm value chains [12]. The carbon footprint sustainability index in palm oil mills was evaluated to measure the carbon emissions at each stage of the process [13]. The multiple oil crops supply chain system was considered to optimise the overall sustainability profile of the oil crop processes [14]. Noble metallic catalysts were used in the production of renewable diesel from palm oil as an alternative energy source to replace fossil diesel [15]. Researches have shown that a carbon emission reduction of up to 73% can be achieved by substituting the conventional fossil diesel with the palm-derived biodiesel [16,17]. Due to the high generation yield, oil palm is classified as the more effective crop in terms of land utilisation, productivity and marketability, which may help to reduce dependency on fossil fuel [18]. Despite that, the European Parliament has voted to ban the usage of palm oil in biodiesel production in the effort to stop deforestation in tropical countries [19]. This further emphasised the importance of achieving and proving that there is sustainable palm oil production for continuous usage and exportation of palm oil-based product.

There are still many challenges in the implementation of the RSPO standard in the palm oil industry. Issues such as lack of information transparency, traceability, the low and unfair premium price for CSPO are some of the major factors that discourage the initiation of CSPO production [20]. Currently, the world is moving towards the Industry 4.0, which focuses on the digital transformation of the industry including the development of automation, smart system, digitalisation, big data analysis, Internet-of-Things (IoT) and artificial intelligence (AI). Industry 4.0 is first introduced at Hanover Fair by Germany as the concept of technology-driven manufacturing process integrated with information and communication technologies to strengthen its national competitive position in manufacturing [21]. Various researches were discussed in a study to incorporate Industry 4.0 to enhance sustainability performance [22]. Implementation of Industry 4.0 concept and technology may be a potential solution to improve the effectiveness of CSPO execution. However, the implementation of such ideas requires a robust and smart system to handle the massive amount of data and variables. There is still a huge gap for the palm oil industry to fully adapt to Industry 4.0, primarily due to the absence of proper guidelines and reference cases for stakeholders at the current stage.

The focus of this paper is to review the palm oil industry from upstream processes (plantation and mill) to downstream markets (food, energy and chemical products) to evaluate the potential implementation of Industry 4.0 technologies in each sector. As Industry 4.0 is relatively new to the palm oil industry, the proposed review process considered any form of Industry 4.0 technologies and development (in palm oil or other industries) that is readily available. The main objective is to identify possible solutions to improve existing palm oil industry processes with Industry 4.0 technologies. To the best of authors’ knowledge, no review has been conducted to relate Industry 4.0 technologies and features with the palm oil industry for food, energy and chemical production. Due to the newness of the scope with lack of real industry application, a brain-storming exercise is adapted in this research with literature support based on Industry 4.0 technologies from other industries and input from the palm oil industry experts. In order to ensure a systematic and all-rounded review, Hazard and Operability Analysis (HAZOP) methodology is adopted. HAZOP is a systematic brain-storming approach used in chemical engineering i) to identify potential process hazard, ii) to assess the ultimate consequence of the cause, iii) to evaluate the adequacy of existing safeguards and mitigations, and iv) to propose recommendations for improvement if required [23]. This approach has shown great potential to identify research gaps and potential implementation in biomass processes [24]. In short, a detailed review of the current palm oil industry is conducted in this work with HAZOP literature review approach by i) identifying the credible process deviations in the palm oil industry, ii) assessing the respective consequences, iii) evaluating current practices to prevent the deviations or to mitigate the consequences, and finally iv) evaluating any possible Industry 4.0 technologies adaptation that can help to rectify the problems in the palm oil industry.

2. Methodology

In this paper, the HAZOP methodology is adopted to identify the potential implementation of Industry 4.0 technologies into the palm oil industry. The HAZOP approach is used in various industries to evaluate process safety and identify potential improvement. The oil and gas industry is actively applying this method to evaluate and improve process safety and control based on piping and instrumental diagrams (P&IDs). Typically, a third party is engaged in the review process to ensure an unbiased evaluation. A study was conducted to compare the industry HAZOP approach and the HAZOP literature review approach, and has successfully incorporated the HAZOP approach into biomass supply chain optimisation model literature review [24]. The same methodology is adopted in this paper to review the possibility of integrating Industry 4.0 technologies into palm-based food, energy and chemical production processes. Fig. 1 shows the proposed procedure for the modified HAZOP
literature review approach designed for this paper.

As per the first step in the procedure, Fig. 2 represents a simplified block flow diagram of the palm oil supply chain used for this study. The overall process was classified into 3 nodes to enable a focused review process. The deviations and guidewords that used to trigger imagination and brainstorming of potential process deviation/hazard in this study are summarised in Table 1. Several assumptions and limitations have been listed prior to the review process, which include i) only single failure/deviation is considered at any time, ii) any form of Industry 4.0 technologies (implemented in existing palm oil and other industries, and developing technologies) are considered in this study, and iii) any form of input (literature, interview, survey, etc.) from industry stakeholders are considered as credible source and information. Deviations and guidewords are used to trigger a structured imagination of possible process upsets or problems. Credible causes and their respective ultimate consequences are also discussed and summarised in worksheets (see Appendix). Upon assessing the problems and consequences in the industry, the team also conducted research based on literature and industry input to identify existing practices or methods that could mitigate/safeguard the problems. The identified problems were related to existing Industry 4.0 technologies and features (that have yet to be implemented in the palm oil industry) to access the potential adaptation which may help to minimise/prevent the problems. The verification of existing technologies was mainly focused on the publications (within 5 years) from the Elsevier database, while some older publications were included if the content is highly relevant to this work [25]. The screening of the literature was conducted based on the keywords identified from the HAZOP recommendations, including palm oil, IoT, weather forecast, soil detection, AI, deep learning, image processing, cloud computing, oil palm ripeness, blockchain, cloud computing, smart contract, cybersecurity, big data analysis, and optimisation. Recommendations were suggested to highlight the possible integration of Industry 4.0 technologies into the palm oil industry as research and development gaps. These recommendations can be adopted by stakeholders as a guideline to study the possible Industry 4.0 implementation and investment for their respective sectors.

3. Results and discussion

A comprehensive HAZOP review was conducted based on the scope presented in Fig. 2. The details of the discussions were recorded and documented in Table A.1, A.2 and A.3 in the appendices. Table 2 summaries all the recommendations proposed from the HAZOP review. These recommendations are the compiled information for potential improvement and implementation of Industry 4.0 technologies into the palm oil industry based on the current industry problems and maturity of Industry 4.0 technologies. A total of 14 recommendations were identified from the upstream processes (Node 1), 8 new recommendations proposed for downstream processes (Node 2) and 1 new recommendation was introduced from market/retailers’ point of view (Node 3). Analysis of the outcomes suggested that some recommendations were interrelated and addressing a similar issue in the palm oil industry, which can be rectified or improved with Industry 4.0 technologies. A total of 8 classes of Industry 4.0 technologies were identified that have the potential to be implemented in the palm oil industry. The following sections discussed the details of each technology and its respective function in the palm oil industry.
3.1. IoT devices-based implementation

Upon analysis and investigation, Recommendations 1 and 2 (summarised in Table 2) proposed from the HAZOP review can be summarised as potential gaps to utilise IoT devices to improve oil palm plantation management. Recommendation 1 (Incorporation of localised IoT devices to improve the accuracy of weather prediction) suggested that IoT devices may help to minimise the impact on production yield and activities due to uncertain weather conditions. Based on the oil palm plantation expert’s comments, harvesting of fresh palm fruit is highly dependent on weather conditions. Currently, daily harvesting activity is planned according to the regional or national weather forecast, which does not reflect the actual condition at the plantation site. Thus, localised devices to detect plantation site parameters for an improved weather prediction system may help to increase the efficiency of plantation management. A study has shown poor labour planning due to inaccurate weather forecast may cause a delay in harvesting, thus subsequently reduces the oil extraction and profit [26]. Various researches were conducted to enhance the local weather prediction model. For instance, an adaptive weather forecasting device based on local temperature, wind speed and global radiation was proposed for agriculture application [27]. The proposed model has shown better accuracy in providing short-term forecasts using local devices, including prediction of seasonal changes based on weather conditions in previous years. Convolutional neural network architecture which capable of conducting accurate weather forecasts based on the collected regional temperature and wind speed to improve the prediction performance [28]. Literature has shown that IoT devices can be implemented into upstream of the palm oil industry to have a better local weather forecast system for more stable harvesting and production planning.

Similarly, Recommendation 2 (Incorporation of localised IoT devices to detect soil properties for moisture and nutrient) addressed the need for local devices to detect and control soil properties, such as nutrients and moisture for optimum plantation conditions. Soil nutrients may be
Table 1

<table>
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<tr>
<th>Deviations</th>
<th>Guidewords</th>
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<tr>
<td>Feed</td>
<td>Fluctuation of quantity Inconsistency of quality Storage Various suppliers</td>
</tr>
<tr>
<td>Processing efficiency</td>
<td>Monitoring of process Process intervention/control Maintenance</td>
</tr>
<tr>
<td>Product</td>
<td>Fluctuation of quantity Inconsistency of quality Storage Product distribution</td>
</tr>
<tr>
<td>Cost</td>
<td>Fluctuation of feed cost Fluctuation of product price Processing cost</td>
</tr>
<tr>
<td>Accuracy of information</td>
<td>Traceability of resources Information security</td>
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Table 2

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<th>Recommendations</th>
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<tr>
<td>Node 1:</td>
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<tr>
<td>1. Incorporation of localised IoT devices to improve the accuracy of weather prediction.</td>
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<tr>
<td>2. Incorporation of localised IoT devices to detect soil properties for moisture and nutrient.</td>
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<tr>
<td>3. AI imaging processing technology to determine tree health status locally.</td>
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<tr>
<td>4. Health care devices such as smartwatches to monitor health status and location of worker.</td>
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<tr>
<td>5. AI image processing technology to determine the ripeness of palm fruit locally.</td>
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<tr>
<td>6. Combined IoT device to detect rippled fruit and cloud computing to optimise harvesting plan/route to save time.</td>
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<td>7. Incorporate IoT and big data analysis on machinery, detectors, controllers to determine optimum repair schedule prior to breakdown.</td>
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<tr>
<td>8. IoT and big data analysis to improve forecasting techniques for fresh palm fruit generation.</td>
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<td>9. Blockchain technology to enhance the traceability of products across the supply chain.</td>
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<td>10. Cloud computing to optimise supply chain network from multiple sources; while all the required quantity, properties, and sustainability profile are achieved.</td>
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<td>11. Smart contract to determine the premium price for good quality products.</td>
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<td>12. IoT devices and GPS system to detect live loading weight and truck location during distribution.</td>
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<td>13. Provide tools for the digitalisation of printed documents.</td>
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<td>14. Improve cybersecurity, such as blockchain for decentralised network.</td>
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<td>Node 2:</td>
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<tr>
<td>15. Improvement of CPO production forecast for more efficient supply chain and storage management.</td>
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<tr>
<td>16. Incorporate smart contract to increase the selling price of fresh palm fruit for SMEs with consistent supply.</td>
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<tr>
<td>17. Incorporation of IoT devices in the process to enable remote monitoring and access for process control.</td>
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<tr>
<td>18. Incorporation of big data analysis, cloud computing and IoT to enable communication between multiple control loop/system for mitigation action upon any control loop failure.</td>
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<tr>
<td>19. Incorporate blockchain and IoT technology to ensure each product is distributed within the maximum allowable storage time.</td>
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<tr>
<td>20. Incorporation of live weather forecast, traffic information and GPS to optimise distribution network.</td>
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<tr>
<td>21. Big data analysis to forecast market demand for each downstream product to plan for production strategy in advance.</td>
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<tr>
<td>22. Big data analysis to improve CPO generation forecast including weather and process conditions to enable more accurate prediction for pricing.</td>
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<tr>
<td>Node 3:</td>
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<tr>
<td>23. IoT and image processing devices to keep track of daily stock count.</td>
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lost through erosion of soil sediments, leaching, runoff (with rainwater), and fresh fruit bunch harvesting activity. Typically, empty fruit bunches are used as mulches to cover the soil around palm trees to preserve nutrients. Research has reported that the EFB mulch could help to increase pH, Nitrogen, Phosphorus, and Potassium content [29]. A balanced nutrient regime for palm tree has shown better yield, especially among small stakeholders [30]. Many efforts have been conducted to evaluate the impacts of fertiliser usage for higher oil yield and better management practices [26,31–33]. Besides, annual soil testing and fertiliser planning are required to maintain good soil condition. Based on the oil palm plantation practice in Malaysia, soil analysis and fertiliser application are typically conducted between January and February to avoid monsoon season (minimise nutrient loss); while a corrective fertiliser application is conducted between July to September. This process may take up to a few weeks with the involvement of intensive labour effort to collect a huge number of soil samples across the plantation sites. A study utilised principal component analysis to demonstrate that geometric enzyme activity, available phosphorus and moisture content are the key factors to determine soil quality in oil palm plantation [34]. This study concluded that soil testing analysis could be reduced to only three parameters. However, despite the potential to develop a smart IoT system to monitor soil conditions, the advantages of this feature may be insignificant due to the relatively low demand and frequency of soil testing and fertiliser activity requirement throughout the production years. A detailed cost and benefit analysis should be conducted prior to the implementation to compare the functionality of the automation soil detection system with the manual soil detection system, especially for the application in SMEs.

A smart plantation system is a more feasible implementation with consideration of multiple factors, include water and soil management to reduce the dependency of labour which improves efficiency and minimises cost. The concept of smart farming is not new to the world as various researches have been conducted. A comprehensive review and comparison of multiple IoT applications in smart farming have been discussed elsewhere [35]. Unfortunately, to date, there is no one-size-fits-all protocol that can perform well in all aspects including latency, energy and bandwidth requirements, throughput, reliability and security. In the view of improving sustainable practice, fuzzy logic control was incorporated into IoT devices to demonstrate a smart water irrigation system [36]. The work showed that implementing IoT in the system can reduce water usage and labour cost. A similar study in an urban application of lawn management also demonstrated the advantages of a smart irrigation system in achieving a more sustainable and environmental-friendly implementation [37]. Researchers concluded that the plant water deficit index threshold could be adopted into IoT devices for smart irrigation scheduling and plant transpiration [38]. Apart from the smart irrigation system, the application of IoT was also adopted for real-time monitoring and control systems in a greenhouse [39]. Despite the advantages of IoT features, large scale implementation of IoT is still considered a challenging task, especially in oil palm plantation management due to lack of internet coverage in many plantation sites and the network speed limitation. Apart from that, IoT devices and sensors should be placed strategically on site for optimum detection coverage and cost. Nonetheless, the advancement of internet and computing services such as 5G network will drive the IoT ecosystem in the business model of a smart enterprise [40]. To note, investment cost of IoT devices should be emphasized in the development phase, especially with the consideration of relatively low investment budget from SMEs.

3.2. Smart forecasting-based implementation

Several requirements for better forecasting tools were identified from the HAZOP review in the aspects of weather, maintenance, production rate and quality, market demand and pricing as shown in Recommendations 1 (Incorporation of localised IoT devices to improve the accuracy of weather prediction), 7 (Incorporate IoT and big data analysis on machinery, detectors, controllers to determine optimum repair schedule prior to breakdown), 8 (IoT and big data analysis to improve forecasting techniques for fresh palm fruit generation), 15 (Improvement of CPO production forecast for more efficient supply chain and
storage management), 21 (Big data analysis to forecast market demand for each downstream product to plan for production strategy in advance), and 22 (Big data analysis to improve CPO generation forecast including weather and process conditions to enable more accurate prediction for pricing) in Table 2. As discussed in the previous section, the dynamic nature of palm oil production is directly affecting the pricing and downstream applications, especially the competitive price comparison between biodiesel and petrodiesel. Therefore, the accuracy of forecasting technology to predict the dynamic production and price of palm oil is crucial for the industry to have more precise management and planning. A series of Industry 4.0-based forecasting technologies are discussed in this section, e.g., the incorporation of big data analysis and deep machine learning. Study shows that a convolutional neural network model can improve forecasting accuracy due to its ability to capture and utilise multi-scale data characteristics [41]. Various machine learning algorithms based on precipitation, maximum and minimum temperature data were applied to model climate changes in Pakistan including artificial neural network, K-nearest neighbour, support vector machine and relevance vector machine [42]. An accurate weather forecast provides a better basis of water and fertiliser management, and hence improves the production yield of palm oil. Researchers adapted Bayesian networks to predict oil palm plantation yield, which shows comparable results to the artificial neural network approach [43].

Forecasting technology can also be applied in the process control and management in the palm oil industry, such as palm oil mill and biodiesel refinery. The need for a preventive measure in the processing was highlighted in Recommendation 18 (Incorporation of big data analysis, cloud computing and IoT to enable communication between multiple control loop/system for mitigation action upon any control loop failure). A comprehensive review was conducted on various AI applications in the management of process maintenance [44]. The study also showed that the genetic algorithm and neural network are the best approaches for preventive maintenance planning and scheduling purpose. Another work was conducted to predict the requirement of maintenance on machine tools using AI techniques based on the machine condition data to reduce unplanned downtime or failure [45]. This technology can be implemented into the palm oil processes, equipment maintenance detection and scheduling system to minimise equipment breakage. For example, detection of mechanical failure in the oil extraction process based on the movement of the pressing machine and prediction of the maintenance schedule for the process control valve in refinery based on the response time degradation. In terms of supply chain and logistics management, researchers have improved the Baltic Dry Index forecasting accuracy with AI method to minimise risk due to changes in shipping freights [46].

Implementation of Industry 4.0 technologies such as big data analysis, neural network and AI have shown the potential to improve the accuracy in forecasting technology. Various researches have shown that adaptation of such technology is possible in plantation, process, and logistics. Nonetheless, for such technology to be integrated into the palm oil industry, significant improvement of the existing equipment and facilities are required. For instance, IoT-enabled sensors have to be installed in plantation sites and processing plants for big data collection and input into the forecasting technology. This may impose challenges for stakeholders, especially SMEs, in terms of affordability due to various uncertainties in revenue and cost [47].

3.3. Smart image processing technology-based implementation

From Recommendations 3 (AI imaging processing technology to determine tree health status locally), 5 (AI image processing technology to determine the ripeness of palm fruit locally), 13 (Provide tools for the digitalisation of printed documents), and 23 (IoT and image processing devices to keep track of daily stock count) in Table 2, the HAZOP review shows that the advancement of image processing tool may help to improve the efficiency of processes in the palm oil industry. In the plantation site, identification of palm tree health status and fruit ripeness has been one of the major process bottlenecks which involve intensive labour and time. Based on oil palm plantation expert, satellite imaging technology can be used to identify unhealthy trees (based on leaf colour) within a large plantation site. Nonetheless, local observation is still required for confirmation, especially for the case where a single (or a small number of) unhealthy tree is surrounded by many healthy trees. Similar smart imaging technology can be implemented for palm fruit ripeness detection. Variation of flowering and ripeness of each palm fruit in the same brunch or tree is very common due to the non-homogenous pollination nature of palm oil [48]. This requires farmers to identify ripped fruits visually at the site for harvesting purpose. Such requirement and practice demand tremendous labour force; and poses a relatively low efficiency. One of the potential adaptations of imaging processing in an oil palm plantation is to use localised imaging system such as CCTV or mobile imaging devices (mobile robotic or drone) for the oil palm ripeness detection. The system should consider the uneven terrain and lighting at the plantation site. However, to the authors’ best knowledge, such a system has yet to be implemented in the palm oil industry.

Despite that, on-going research and development to integrate smart image processing technologies into oil palm process had been conducted. A mobile robot was built to scan and identify palm tree trunk in plantation sites using colour image processing and depth data processing techniques [49]. Detection of palm fruit ripeness by the red, green and blue (RGB) colour unit from the image captured was investigated [50]. Similarly, a low-cost oil palm ripeness detector was constructed using a digital camera and laptop to detect RGB of palm fruit placed in a small chamber [51]. On the other hand, the incorporation of smart imaging detection and computational power is required to accurately detect and predict ripeness of palm fruit for harvesting planning. Study shows that palm fruit ripeness can be detected with genetic algorithm neural network based on near-infrared spectral data [52]. An artificial neural network model was developed to detect ripeness of fresh fruit bunch via hue, saturation and intensity colour model. The result shows that the accuracy of the artificial neural network model is higher as compared to the linear regression model [53]. A deep learning model to classify tree species can be modified to classify palm trees (with fruit and without fruit) for harvesting purpose [54]. Further improvement of the smart imaging processing technology can be achieved by integrating the detection system with IoT and cloud computing as proposed in Recommendation 6 (Combined IoT device to detect ripped fruit and cloud computing to optimise harvesting plan/route to save time). Unhealthy trees or palm fruit ripeness can be detected with IoT-enabled detection robot or drone where the information can be processed in a centralised cloud computing server for analysis. For instance, the smart detection system can be used to propose an optimum harvesting route for farmers to reduce the harvesting period or to recommend an optimum schedule for the tree health check.

Apart from oil palm plantation site, the implementation of image processing technology also can be applied in palm oil processing such as biodiesel refinery. One of the applications includes detection of defects on process equipment and product to improve the efficiency of maintenance activities and quality checking processes. Research has successfully developed a deep learning model to detect piping defect via CCTV footage [55]. Implementation of such a detection system may help to prevent unpredicted piping failure, especially for hazardous process piping and equipment. A comprehensive review of the application of non-destructive sensors to detect horticultural products and the application of machine learning was conducted as part of the detection tools to improve the accuracy of the system [56]. Image processing technology can also be applied in the retailer operation as suggested from HAZOP Recommendation 23 (IoT and image processing devices to keep track of daily stock count). For instance, unmanned retailer shop or stock-check process using CCTV and sensor to detect changes of palm oil
product on the shelf. This idea has been demonstrated in a study of real-time recognition system to detect and track products in the cabinet [57]. Complex smart tracking technology can further be improved by incorporation of demand forecasting based on the product flow detection on the shelf to manage stock replenishment accurately. For example, the production rate of palm biodiesel is planned according to the demand of biodiesel to avoid over or under production to maintain a healthy biodiesel price.

Development of image processing technology helps in the digital transformation of the palm oil industry and its operations. Information transfer and documentation such as specification sheet (or datasheet) of palm oil product, checklist for maintenance, etc., are usually in hard-copies, especially among SMEs. One of the reasons that many stakeholders are reluctant to put extra effort into Industry 4.0 is due to the tedious transition period, such as digitalisation of system that includes converting historical data from hardcopy into softcopy. This creates an additional barrier for the advancement of the palm oil industry into the Industry 4.0 era. The issue was highlighted in Recommendations 13 (Provide tools for the digitalisation of printed documents) where a smart system is needed to aid the transformation towards the paperless system. This paper has identified several researches to improve the efficiency of translating hardcopy documents into softcopy via image processing. For example, a deep learning system was constructed to detect row of sentences within a written document for better digital translation results [58]. Similar work was conducted to recognise different languages to cater to different nationalities of workers. For example, English handwritten word image identification was conducted based on Arnold transform approach to recognise and record written documents in softcopy, while similar work was undertaken to recognise written Chinese characters [59,60]. Adaptation of such technology may help to promote more initiatives from palm oil industry stakeholders to move towards Industry 4.0. Nevertheless, the system should uphold a proper security system to avoid leakage of sensitive information. This issue will be addressed with cybersecurity in Section 3.8.

3.4. Cloud computing-based implementation

Previous sections had discussed various potential implementations of Industry 4.0 technologies in the palm oil industry, including localised IoT devices, forecasting and smart image processing. The operation of such technologies requires a considerable amount of computing power for big data analysis and AI processing. This creates a challenge among palm oil industry stakeholders, especially SMEs, which do not have advanced computing facilities in their conventional operation. Cloud computing technology is one of the Industry 4.0 technologies which enables multiple users to access a centralised powerful computing machine with dynamic and reconfigurable computing applications. The applications include remote access for information sharing, editing and storage, database management, and processing large datasets for complex problems [61]. There are various types of cloud computing, including private cloud, public cloud, community cloud and hybrid cloud with their respective features and applications [62]. The main advantage of cloud computing is that it allows users to send the raw data remotely to the cloud server for complex data processing, then the processed result is delivered back to the users. This enables users to access powerful computing facility with a minimum cost of subscription for the service to avoid huge investment cost into physical computing facility. This feature could be a more favourable option to the palm oil industry, especially SMEs in the plantation. A study has shown that migration to the cloud server for data storage and computing helps the organisation by reducing capital and operational cost, improve flexibility, and increase revenue, especially among SMEs [63]. Nonetheless, accessibility of cloud computing depends on internet access and connectivity, which is a common facility readily available in the palm oil industry, except in rural plantation sites.

Various applications of cloud computing have been implemented across many industries and problems. A study was conducted by using a free cloud computing platform and image processing technology from Google Earth Engine to classify the oil palm plantation map into water, built-up, forest, bare soil, oil palm, paddy and other vegetation [64]. Nonetheless, distinguishing oil palm plantation with other vegetation from Google Earth image has proven to be a challenging work due to the similarity in spectral image and structure [65]. Complex process optimisation in palm oil processing plants can be solved with cloud computing to reduce the investment cost. An artificial neural network model was used to optimise a molecular distillation column in the palm oil refinery process based on feed flow rate, column temperature and pressure to optimise beta-carotene, tocopherol and free fatty acid concentration in the outlet stream [66]. Production of palm oil derived cellulose phosphate is optimised by evaluating the reactor parameter using wavelet neural network with a prediction error of less than 7% [67]. Palm oil mill operating conditions were optimised via genetic algorithm and artificial neural network to ensure the plant emissions are within the allowable limit [68]. These high computational demanding optimisation model via deep learning and artificial neural network can easily be implemented by SMEs with cloud computing to minimise investment costs.

Other efforts and advantages of cloud computing also have been exploited by researchers for its application in other sectors which can be incorporated into the palm oil industry. For example, a study shows that cloud computing performs well in solving the fuzzy problem of a trust-based access control model, which can be applied in the palm oil industry to model trust issues among SMEs in plantations [69]. For example, the model can be used in the planning of oil palm supply chain based on the consistency and on-time delivery of oil palm from various SMEs to avoid inadequacy of feedstock at the palm oil refinery. A detailed review of cloud computing integration into supply chain system shows improvement in efficiency and effectiveness, such as improved communication and real-time information sharing [70]. Natural hazard modelling system takes advantage of cloud computing as an easily scalable computational power to handle increasing data collection from various IoT detection system [71]. Similar applications can be incorporated with localised weather forecast devices in oil palm plantation to compute local weather forecast and production yield using a cloud computing platform, as discussed in Section 3.1. In order to reduce data handling in cloud computing, a review of various scheduling approaches shows that parameters such as response time, reliability, availability, cost, and energy consumption are the key factors to implement cloud computing [72]. Apart from the many applications of cloud computing, researchers also focus on increasing the connection speed. For example, edge and fog computing are developed to reduce the latency of the cloud computing network [73]. These research efforts are essential to enhance the feasibility of implementation of cloud computing in the palm oil industry, especially for the upstream processes like plantation sites, where internet accessibility and reliability could be the bottleneck of the system.

3.5. Smart monitoring devices-based implementation

Advancement of Industry 4.0 technologies improves the traditional monitoring system by reducing the requirement of manual operation and labour. For instance, the features discussed in Sections 3.1–3.3 involved various IoT devices that used to detect the process parameters and shared to the centralised system. Incorporation of IoT devices also enables remote monitor and control of the process parameters. For example, oil palm ripeness, palm tree health, water management at the plantation site and process parameters in the palm oil refinery can be accessed outside of work premises for better management efficiency. Those suggestions are reflected in Recommendations 3 (AI imaging processing technology to determine tree health status locally), 5 (AI image processing technology to determine the ripeness of palm fruit locally) and 17 (Incorporation of IoT devices in the process to enable...
remote monitoring and access for process control). Apart from the process monitoring system, this section discusses the potential implementation of smart monitoring devices on personnel. From industry feedback and discussion, several cases were found that employees left their working position outside of the company compound during office hours without consent from superior. This is critical in the oil palm plantation due to the harvesting efficiency is heavily dependent on the availability of labour. Global Positioning System (GPS) tracking function from the company issued smartphone was used to trace staff locations during an emergency, especially when the staff on duty cannot be reached. However, there is a loophole of this system, where unethical employees can intentionally leave their smartphone in their office while they are physically away from their position. One of the alternative options to improve the monitoring system is by means of smart wearable devices such as smartwatches.

The current state of smartwatch technology not only can track the user’s location via GPS but also incorporate healthcare functionalities which can be used to monitor users’ health conditions. Oil palm farmers are usually exposed to various working hazards such as hot weather that may lead to dehydration, heavy lifting, potential injuries due to sharp objects at plantation site or snake bite. This issue can be rectified with biosensor embedded in a smartwatch to track the user’s activity from heart rate assessment, movement detection and GPS information. For example, operators’ heart rate can be monitored during operation in plantation and processing plants to ensure good health status and wearable sweat sensors can be incorporated to detect the physical state of the wearer with health diagnostics [74,75]. Smartwatches were also developed to detect falls, thus allowing first aid response teams to arrive at the scene swift when the farmer or user has been determined to have had a serious accident, especially during operation at height [76].

Apart from that, wearable biosensors have been slowly introduced in the healthcare industry to provide a unique personalised healthcare plan to suit individual needs based on their health conditions [77]. Tracing the operators’ activity via biosensor in smartwatch will not only enhance safety feature but can also be incorporated with insurance policy based on the specific activity performed by operators with a robust tracking system and record.

With the regular monitoring and recording, application of smart monitoring system can be extended to various aspects. For example, smart monitoring to improve product traceability which will be discussed in detail in Section 3.6. Besides, a smart contract between multiple stakeholders can be implemented, such as a dynamic incentive reward and healthcare coverage system based on farmers daily working activity from plantation and processing plants to ensure good health status and location of worker) in Table 2, a more efficient and fair distribution of the healthcare benefits. Further discussion on the smart contract application will be presented in Section 3.7.

3.6. Traceability-based implementation

As discussed earlier, traceability of palm oil source is one of the key challenges to promote CSPO due to the limitation of the current system to differentiate sustainable and non-sustainable palm oil from the huge amount of SMEs involved in the supply chain [8]. Besides, prolonged storage of palm fruit and oil will affect the oil extraction yield. These issues were addressed in the HAZOP Recommendations 9 (Blockchain technology to enhance the traceability of products across the supply chain) and 19 (Incorporate blockchain and IoT technology to ensure each product is distributed within the maximum allowable storage time). The recommendations suggested that the traceability of palm oil-based products needs to be improved. In order to prove the palm oil is sustainable, a robust tracking system that records the product lifecycle is required to show the environmental impacts from each process. For proper recording and tracking purposes, blockchain has shown an excellent capability to process and broadcast various data along the product lifecycle to enable information and service sharing across enterprises [78]. Blockchain is a shared, distributed, and synchronized ledger that comprised of unchangeable and digitally recorded data in blocks, which can facilitate transaction recording and assets tracking in a business network [79]. This can be applied in the palm oil industry to keep track of all palm oil-based products across each process to fulfill the standard requirement, such as CSPO and HALAL certification. Study shows that blockchain was used to improve supply chain management in terms of traceability, fragmentation of the system, and capability to deal with real-time information (sharing and control) [80].

For better security, blockchain technology should be embedded with IoT devices such that the information captured by the IoT devices (such as sensors) will be stored directly into the blockchain system to avoid manual tempering by individuals. Researchers have conducted studies to improved traceability of wearable IoT devices for healthcare service to enhance privacy preservation, compromise detection and provide the ability for audit tracing [81]. With the idea of incorporating IoT devices to improve traceability as shown in Recommendation 12 (IoT devices and GPS system to detect live loading weight and truck location during distribution), an IoT weight sensor can be installed in a delivery truck to trace the weight of palm oil products and the truck location. This concern was raised during a discussion with oil palm plantation manager where they claimed is one of the potential issues in the supply chain of fresh fruit bunches. Currently, all fresh palm fruits are weighted before departure from the plantation site, and the weight is measured once again at processing mill upon arrival to confirm the exact sales amount. Often the amount is not tally due to potential losses during transportation or thievery. The incorporation of IoT weight and GPS sensors on delivery trucks may aid to minimise this problem. For example, if weight losses are detected when the truck is in motion, most likely the losses may occur due to transportation issues such as sharp corners, bumpy road conditions or speeding. On the other hand, if the weight losses are detected when the truck is in station mode or the truck location deviates from the planned route based on GPS detection, an investigation can be initiated for potential theft.

A similar type of application has been studied to improve traceability by IoT devices. For instance, a radio-frequency identification system is used in a container logistic system to identify different transport units for monitoring and management purposes, improve efficiency, and prevent container loss [82]. A study based on wood furniture supply chain concluded that the investment cost for product tracking system should be equitable distributed among all stakeholders to improve the feasibility of implementation [83]. With such traceability capability from Industry 4.0 technology, a more robust tracking system for CSPO can help to tackle the issue of palm biodiesel production in the European countries.

3.7. Smart contract-based implementation

A smart contract is the concept of an autonomous system that is designed to conduct a transaction without human intervention. It is usually coded parameters written into the blockchain to perform specific transaction if certain requirement or condition is met prior (contractual) agreement from all parties [84]. Smart contract applications are also included in IoT, system security, and reduce the financial risk [85]. For example, incorporation IoT and smart contract to enable automated transactions or dedicated payment schemes. In line with the Recommendation 4 (Healthcare devices such as smartwatches to monitor health status and location of worker) in Table 2, a more efficient and fair payment system can be programmed based on farmers’ health condition and activity pattern in plantation to replace the conventional daily fixed rate scheme. Such implementation can be used to differentiate committed employees from uncommitted employees and provide an adequate reward (or penalty), respectively. From Recommendation 11 (Smart contract to determine the premium price for good quality
products) and 16 (Incorporate smart contract to increase the selling price of fresh palm fruit for SMEs with consistent supply), different pricing of crude palm oil (CPO) based on its properties, quality, and consistency of supply can be embedded into a smart contract to ensure a consistent supply of premium palm oil, especially from SMEs. Farmers that are able to produce premium palm oil that fulfils CSEO standard will be automatically awarded the premium price in the smart contract system to encourage SMEs to initiate CSEO certification and continue with CSEO production.

Similar to the traceability function discussed in Section 3.6, a robust smart contract system should be incorporated together with IoT-enabled devices to allow for automatic data monitoring and recording to avoid error from manual operation. For example, IoT-enabled containers are utilised to monitor shipment conditions including temperature, location, pressure (for open/close detection of a pressurised container), and acceleration for sudden fall or drop detection [86]. If any of the sensors detected violation of the agreed shipping condition, the information could be used to adjust the shipping cost as per the smart contract agreed by all stakeholders. This can be translated into the palm oil industry where any unsustainable practice (e.g., deforestation which increases carbon release) is detected, the premium price of CSEO will, therefore, not be awarded. Application of smart contract in a blockchain-based platform has shown promising results to improve the efficiency of instant decision making and support for a better quality of product and service [78]. Execution of transactions can be automated for an on-spec product, and terminated if the product is found to be faulty in any process stage. Payment system for cloud services with smart contract incorporation was evaluated in a study. Two models were proposed, including a proof-based verification model which only feasible if all parties are assumed to be honest; and a replication-based verification model which works best when fines are imposed to cheating party [87]. The concept of Game Theory is incorporated into a model to mitigate cheating and illegal behaviour to reduce the success rate of criminal smart contract [88]. Another study discussed the application of smart contract in an autonomous delivery system which includes consideration of supply chain performance, legal aspects and product customisation [89]. The smart contract also can be incorporated into financial loan management where this technology can be beneficial to handle subsidies or loan among SMEs [90]. For example, the loan interest rate is imposed based on CSEO certification status to promote the initiation for CSEO certification where a lower interest rate will be imposed for those companies that are committed to fulfil the standard.

3.8. Cybersecurity-based implementation

Despite the advantages of applying Industry 4.0 technologies to improve process efficiency, the system may be exposed to higher security threat due to the interlinked nature of infrastructure. Cybersecurity issues are related to several types of cyber-attacks, including viruses, Trojan horse, worms, phishing, Denial-of-Service attack, illegal access and control system attacks [91]. If any form of cybersecurity threat manages to infiltrate the system of IoT devices, the rest of the inter-linked devices are prone to the risk of sabotage as well. This problem has been addressed in the HAZOP review in Recommendation 14 (Improve cybersecurity, such as blockchain for decentralised network). Numerous researchers have proposed various methods to evaluate and strengthen cybersecurity. A threat model is proposed to conduct a risk analysis of an IoT system to assess cyber threats and propose countermeasures [92]. Blockchain technology is incorporated into the healthcare system to address the concern of information leakage due to the decentralised nature of the blockchain system that resists to cyber hack [93]. Various approaches have been discussed to improve security issues in cloud, edge and fog computing platforms [94]. Blockchain technology can also be incorporated with smart contract system to enhance operational security in battery energy storage system from cyber-attack. The simulation result shows significant improvement as compared to centralised or multi-agent distributed architectures [95]. A five-level trust model is proposed for cloud-edge based infrastructure to allow data owners to determine the trust level of each party. This increases the flexibility of the model to react differently in cases which trust level can be adjusted based on specific action or performance [96]. As a robust and high-end cybersecurity system can be very expensive, a study proposed an attacker-defender model to evaluate the strategy for defending assets in a digital logistic network [97]. Similarly, Game Theory has been applied to evaluate and optimise cloud security level and its pricing strategy [98].

From the discussion, numerous efforts have been made by researchers to ensure safe implementation of Industry 4.0 technologies. Simultaneous implementation of cybersecurity and other Industry 4.0 technologies in the palm oil industry should be performed i) to avoid the introduction of new forms of threat, and ii) to minimise operational risk in future. However, based on industry input, the processing information and knowledge in the palm oil industry are typically standard across different companies. Less effort and investment have been used to improve the security of information protection, except for the protection of research and development information due to potential patent generation that may provide significant income to the company. Thus, any form of cybersecurity measure should be given priority to the protection of the research and development department during the transformation of Industry 4.0 in the palm oil industry.

4. Potential Industry 4.0 implementation in the palm oil industry

HAZOP approach is generally used in the chemical engineering industry to review and improve process safety based on P&IDs. A new version of P&ID is produced to incorporate practical recommendations from the HAZOP review to reflect the changes for design improvement. By adopting the same philosophy, an updated block flow diagram (based on Fig. 2) is proposed to reflect the potential Industry 4.0 technologies implementation in the palm oil industry, as shown in Fig. 3. The proposed potential implementations are based on the discussion of various Industry 4.0 technologies in Sections 3.1–3.8. A total of 13 Industry 4.0 features have been proposed. These features include general features that can be implemented across all stakeholders (Feature 1 to 3) and specific features that can be adapted in particular process stages (Feature 4 to 13). These features are proposed to tackle the current challenges in the palm oil industry including traceability of CSPO, inaccurate forecasting, poor labour and soil nutrient management, unplanned process downtime, safety and healthcare [26,29,45,81,99].

Feature 1 (Smart contract for fair pricing) in Fig. 3 suggests that blockchain technology can be implemented across all stakeholders, from upstream palm oil processes to downstream market to improve product lifecycle traceability and transaction security [78,93]. If blockchain technology is implemented across all the palm oil industry stakeholders, an industry-wide smart contract can be configured. An Industry 4.0 enabled industry can systematically generate fair transactions among stakeholders based on their product sustainability performance, CSEO certification, the carbon footprint from processes and logistics, and social impacts. Premium price or subsidy will be awarded or removed depending on the traceable parameters. The improved traceability function is critical to convince users, especially for palm biodiesel production and usage in European countries, to show that the product lifecycle is fulfilling the required sustainability standard. Feature 2 (Traceability of product losses) proposes a product tracing system for logistics to avoid thievery, as discussed in Section 3.6. This will be relatively easy to be implemented by a logistics company by installing IoT-enabled sensors in delivery trucks or containers [82,83,89]. On the other hand, the tedious digitalisation of printed documents creates reluctance for SMEs to adopt Industry 4.0 revolution. As such, the review suggests using AI and deep learning technology in image processing to digitalise document as presented by Feature 3 (Digitalisation of
old documents) [58,100]. This feature is applicable to all stakeholders in the palm oil industry as a supporting feature during the transition period toward Industry 4.0.

Other features proposed from this study are more suitable to improve specific palm oil processes, as shown on the right-hand side of Fig. 3. By incorporating IoT devices and cloud computing at oil palm plantations, the efficiency of plantation management can be improved. Feature 4 (Smart CPO production forecast) suggests that an enhanced forecast system can be used for better yield prediction by installing IoT devices for local weather; and soil detections to induce smart farming for better water and fertiliser management, as suggested by Feature 5 (Smart farming/irrigation) [27,36]. The data processing is proposed to be conducted via cloud computing due to the consideration of relatively low accessibility to powerful computing facilities at the plantation site. Features 6 (Improve harvesting planning/forecast) and 7 (Optimum harvesting route) are proposed to improve the efficiency of palm fruit harvesting at the plantation site. The installation of IoT imaging devices to detect the ripeness of palm fruit has been conducted by various researchers [49–51]. By combining the IoT devices at plantation sites for weather forecast and palm fruit ripeness detection, a more accurate harvesting plan can be prepared to reduce labour cost as proposed in Feature 6. A recent study suggested an inductive sensor system with up to 100% accuracy in detecting palm fruit ripeness and an accurate estimate of harvest time [101]. By combining the IoT devices at plantation sites for weather forecast and palm fruit ripeness detection, a more accurate harvesting plan can be prepared to reduce labour cost as proposed in Feature 6. A recent study suggested an inductive sensor system with up to 100% accuracy in detecting palm fruit ripeness and an accurate estimate of harvest time [101]. This feature can be further improved by incorporating AI and deep learning technology to optimise harvesting route which aims to minimise the distance travelled by farmers within the plantation site as proposed in Feature 7 (Optimum harvesting route) [102,103]. Optimisation of palm fruit harvesting route is similar to handling cold supply chain that the transported material’s quality will deteriorate over time [104]. Feature 8 (Smart contract for price pricing/salary) introduces wearable IoT devices with biosensors to monitor the health conditions and activities of farmers at plantation sites [75,76,105,106]. Such devices can be configured with smart contracts where the workers are awarded and insured based on their daily performances such as effectiveness in harvesting, duration of unplanned break time, awareness to safety, and health status. This feature is not recommended to be implemented in the downstream processing plants because palm oil mill and refinery plant are usually operated in a more defined boundary where supervision of workers is relatively easier as compared to plantation sites.

Other Industry 4.0 technologies can be incorporated into downstream processes such as palm oil refineries to produce refined, bleached and deodorised palm oil for palm biodiesel, food, and chemicals production. Feature 9 (Dynamic process optimisation) proposes a dynamic process optimisation and control system to improve the efficiency of the processes. This requires the installation of IoT sensors in the processes and computational facilities to analyse the dynamic fluctuation of big data. For example, in biodiesel production from palm oil and waste frying oil, the mixing ratio of the oils can be optimised based on the dynamic changes of the feed properties and produced biodiesel properties [107]. Other alternative improvements include the optimisation of the transesterification process in palm biodiesel production based on methanol to oil ratio, amount of catalyst, reaction temperature, and energy efficiency improvement [108]. With IoT sensors installed across the processing system, two additional features can be configured as stated in Feature 10 (Equipment defect detection) and 11 (Remote access of process control). Feature 10 proposes a defect equipment detection system to enable smart maintenance management to minimise unplanned downtime [44,45]. A more advanced detection system may utilise image processing technologies (e.g., photography and CCTV) to determine any piping defect within the process plant, as discussed in Section 3.3 [55]. Utilising the connection of IoT sensors with the control system, remote access to the system can be configured as suggested in Feature 11. This may reduce the requirement of senior engineer at the palm oil processing plant, especially during the night shift. As a result, the overall operation cost can be minimised; while enabling quick remote respond during an emergency. Next, Features 12 (Smart restock notification) and 13 (Smart production management) are proposed to...
install imaging processing and IoT devices to monitor the flow of palm-based products at the retailer market. This aims to create a smart marketing system where automated product replenishment can be configured. In an ultimate scenario where the processing plants and markets are connected with IoT systems, smart production planning can be created to avoid oversupply or undersupply of palm-based product and storage requirement can be minimised.

From the discussion, the majority of the proposed Industry 4.0 features require the integration of IoT devices. Due to the interconnected nature of IoT system, the enhancement of cybersecurity of the palm oil industry should be given priority in the transformation. This should be highlighted to protect information breaches such as research effort, potential patent, personnel information (from wearable IoT devices), CCTV footage, and process sabotage.

5. Conclusions

This paper implemented a HAZOP approach to review the current state of the palm oil industry in Industry 4.0 revolution and development. The state-of-the-art HAZOP review approach provides an in-depth investigation of the system using a guidewords-based brainstorming evaluation method. A total of 23 recommendations were proposed to highlight the potential gaps to incorporate Industry 4.0 technologies in the palm oil industry, including the use of IoT devices, smart image processing technology, smart monitoring, smart forecasting, cloud computing, traceability, smart contract, and cybersecurity. Analysis from the review suggested that the combination of several Industry 4.0 technologies is required. For example, the combination of IoT devices and cloud computing can enable smart CPO production forecast; while the combination of IoT devices, image processing and cloud computing can optimise harvest route in oil palm plantation. This study had identified a total of 13 potential Industry 4.0 features to be implemented across all or specific palm oil industry stakeholders. A mapping diagram was presented to show the possible improvement across the supply chain of palm-based products. Several proposed features are beneficial for the industry as a countermeasure to the movement of banning palm oil usage in European countries due to the sustainability issue. Blockchain technology from Industry 4.0 provides a secure transaction and data recording to improve the traceability of the products. The implementation of such technology across palm oil industry stakeholders offers a robust traceable system to develop sustainable profile and certification of the product. This helps to promote CSPO production, and consequently increase sustainable palm biodiesel production. Nonetheless, investment into IoT sensors for detection and data collection is necessary for the Industry 4.0 transformation. In order to analyse the massive amount of data from IoT devices, cloud computing was proposed for big data analysis instead of physical computing facilities due to almost none of the existing oil palm plantation and processing plant has adequate computing capability for AI and big data analysis. The imaging processing technology was proposed to improve the operational efficiency, such as detection of fruit ripeness and faulty equipment.

In conclusion, this review paper has demonstrated the advantages of HAZOP review approach in evaluating the status of the palm oil industry in the revolution of Industry 4.0. This article discussed the current problems and the conventional mitigation measures in the palm oil industry and explored the possible application of new Industry 4.0 technologies to improve the system. Nonetheless, the review was limited to a macro-level of analysis for each stage of processes. A more detailed consideration can be incorporated in future work. Instead of performing a black box review of each process stage (e.g. the refinery), a more detailed HAZOP literature review can be conducted to include various process systems or equipment to provide a more holistic implementation of Industry 4.0 features in the palm oil industry. Palm waste such as palm biomass can also be included in a future study to understand the overall footprint and the challenges toward palm oil industry 4.0.

CRediT authorship contribution statement

Chun Hsiong Lim: Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. Steven Lim: Investigation, Resources, Funding acquisition. Bing Shen How: Investigation, Resources, Writing - review & editing. Wendy Pei Qin Ng: Investigation, Resources. Sue Lin Ngan: Investigation, Resources, Writing - review & editing. Wei Dong Leong: Investigation, Resources. Hon Loong Lam: Investigation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table A.1
HAZOP worksheet for Node 1

<table>
<thead>
<tr>
<th>Node 1</th>
<th>Description:</th>
<th>Palm oil upstream process including plantation, harvesting and milling</th>
<th>Deviation</th>
<th>Guideword</th>
<th>Causes</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Feed</td>
<td>Uncertainty of weather affecting plantation yield and harvest activities.</td>
<td>1. Unhealthy palm tree.</td>
<td>1. Fluctuation of quantity</td>
<td>1. Harsh weather leading to low production yield.</td>
<td>1. Regional weather prediction model based on satellite data, sea water level, sea buoys, etc.</td>
<td>1. Incorporation of localised IoT devices to improve the accuracy of weather prediction.</td>
<td></td>
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<tr>
<td>2. Non-optimum water/fertiliser usage.</td>
<td>1. Too much or too little supply of water/nutrient resulting lower yield of oil.</td>
<td>2. Over supply of water/fertiliser resulting higher unnecessary cost.</td>
<td></td>
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<tr>
<td>2. Inconsistency of quality</td>
<td>1. Old tree causing low fruit yield, resulting in non-optimum yield.</td>
<td></td>
<td></td>
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</table>
| 4. Al imaging processing technology to determine tree health status locally. | | | | | | (continued on next page)
Table A.1 (continued)

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Guideword</th>
<th>Causes</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Storage</td>
<td></td>
<td>1. Temporarily storage/piling of fresh fruit at plantation for transportation to mill</td>
<td>Optimal production rate vs cost</td>
<td>1. Consistent and proper management of supply chain, such as all harvested fruits are to be processed at mill within 6–24 h.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Inability to timely arrive fresh fruits to mill</td>
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<tr>
<td></td>
<td></td>
<td>3. Inability to timely arrive fresh fruits to mill</td>
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<tr>
<td></td>
<td></td>
<td>4. Inability to timely arrive fresh fruits to mill</td>
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<tr>
<td>4. Various suppliers</td>
<td>Not applicable</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2. Processing efficiency</td>
<td>1. Monitoring of process</td>
<td>1. Lack of monitoring/supervision during plantation and harvesting process.</td>
<td></td>
<td>1. GPS tracking via smart phone to locate personal (usually limited to supervisor position and above with company phone).</td>
<td>4. Health care device such as smartwatches to monitor health status and location of worker.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Inability to detect unsafe working environment for workers</td>
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<tr>
<td></td>
<td></td>
<td>3. Ineffective forecast (based on observation of fruit ripeness) leading to inefficient planning and cost/resource management</td>
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<tr>
<td></td>
<td></td>
<td>4. Ineffective forecast (based on observation of fruit ripeness) leading to inefficient planning and cost/resource management</td>
<td></td>
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<tr>
<td>2. Process intervention/control</td>
<td>1. Refer to fluctuation of water/fertiliser usage above that affect product quantity and quality.</td>
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<td></td>
<td></td>
<td>2. Complex harvesting plan and scheduling of workers across the plantation field.</td>
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<tr>
<td></td>
<td></td>
<td>3. Inability to detect unsafe working environment for workers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Maintenance</td>
<td>1. Breakdown of tools, machinery or vehicle.</td>
<td>1. Delay of process resulting losses in production and off-spec product.</td>
<td></td>
<td>1. Scheduled monitoring and checking of tools condition.</td>
<td>5. AI image processing technology to determine ripeness of palm fruit locally.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Inability to detect unsafe working environment for workers</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>3. Inability to detect unsafe working environment for workers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Product</td>
<td>1. Fluctuation of quantity</td>
<td>1. Inability to detect unsafe working environment for workers</td>
<td></td>
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<td></td>
<td></td>
<td>2. Inability to detect unsafe working environment for workers</td>
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<td>3. Inability to detect unsafe working environment for workers</td>
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<td>4. Inability to detect unsafe working environment for workers</td>
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<td>5. Inability to detect unsafe working environment for workers</td>
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<td>6. Inability to detect unsafe working environment for workers</td>
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</tr>
<tr>
<td>2. Inconsistency of quality</td>
<td>1. Different plantation and harvesting practice among farmers giving different sustainability standard of product (such as impact to environment including deforestation activity, water usage, fertiliser impact).</td>
<td>1. Non-sustainable farming practice leading to negative impact to environment.</td>
<td></td>
<td>1. Sustainable palm oil campaign and certification such as Malaysia Sustainable Palm Oil (MSPO) to ensure high quality of palm oil sources.</td>
<td>9. Blockchain technology to enhance traceability of products across the supply chain.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Difficulty to trace/ensure sustainable practice among small and medium-sized enterprise farmers.</td>
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<td></td>
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<td>3. Inability to detect unsafe working environment for workers</td>
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<td>4. Inability to detect unsafe working environment for workers</td>
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<td>5. Inability to detect unsafe working environment for workers</td>
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<tr>
<td></td>
<td></td>
<td>6. Inability to detect unsafe working environment for workers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 2. Changes of physical and chemical properties of | 1. Lower grade of fruit bunches may potentially cause off- | | | 1. Pretreatment on all palm fruit bunches are conducted to | 11. Smart contract to determine the premium (continued on next page)
Table A.1 (continued)

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Guideword</th>
<th>Causes</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Node 1</strong></td>
<td><strong>Palm oil upstream process including plantation, harvesting and milling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td></td>
<td>harvested palm oil fruit bunches (for example due to weather condition).</td>
<td>spec-contamination of palm oil.</td>
<td>minimise chances of off-spec product.</td>
<td>price for good quality products.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Unfair costing (same selling price across different quality of fruit bunches).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Storage</td>
<td>1. Quality degradation of palm oil fruit bunches due to prolong storage.</td>
<td>1. Long storage promotes bacteria growth, resulting off-spec product.</td>
<td>1. Pretreatment such as sterilization in milling process to minimise impact of microorganism.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>2. Prolonged delivery time reduces quality of fresh palm fruit (increased of FFA and bacteria) leading to potential off-spec product.</td>
<td></td>
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</tr>
<tr>
<td>4. Product distribution</td>
<td>1. Unable to deliver product on time.</td>
<td>1. Loss of fresh palm fruit during transportation (due to insecure loading or thievery) leading to profit losses.</td>
<td>1. Truck loading weight check prior departing from plantation and upon receival at mill to determine losses during transportation.</td>
<td>12. IoT devices and GPS system to detect live loading weight and truck location during distribution.</td>
<td>Previous Recommendations 8 and 11 are applicable here:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Unable to trace fruit losses during transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Cost</td>
<td>1. Fluctuation of feed cost</td>
<td>1. Higher cost of organic fertiliser compared to inorganic fertiliser.</td>
<td>1. Potential high risk of investment into new type of fertiliser without justified return.</td>
<td>1. Partial testing of new fertiliser to compare and monitor the improvement, such as oil yield to minimise investment risk.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Fluctuation of product price</td>
<td>1. Dynamic price of CPO.</td>
<td>1. Forecasting of palm oil production to estimate CPO price in future for planning purpose.</td>
<td>Previous Recommendations 8 and 11 are applicable here:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. Potential changes of palm fruit bunches price leading to unsecure or unfair pricing from dealers.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>2. Unable to differentiate prices for different quality of product</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Processing cost</td>
<td>1. Unplanned shutdown of process.</td>
<td>1. Emergency shutdown or less feed scenario leading to higher production cost to maintain utilities supply, especially boilers. However, the effect is less significant as majority of palm oil mill is using EFB as boiler feed.</td>
<td>1. Current practice to ensure adequate amount of EFB to be stored to maintain boiler operation for specific duration as per company operation philosophy.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>2. Information security</td>
<td>1. Leak of existing process/technology information, however this is considered low impact as technology in oil palm plantation and harvesting is relatively standard and well published.</td>
<td>1. Private and confidential contract with employees.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Leak of research and development information.</td>
<td>1. Potential significant losses in R&amp;D, such as patent.</td>
<td>2. Encrypted computer/laptop to avoid information extraction or sharing prior approval.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>13. Provide tools for digitalisation of printed documents.</td>
<td></td>
<td>Previous Recommendation 9 is applicable here:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9. Blockchain technology to enhance traceability of products across the supply chain.</td>
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<td></td>
<td></td>
<td>14. Improve cybersecurity, such as blockchain for decentralised network.</td>
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</tbody>
</table>
## Table A.2
### HAZOP worksheet for Node 2

**Description:** Processes of palm oil including refinery, bio-diesel production, and food/pharmaceutical production

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Guideword</th>
<th>Causes</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Feed</td>
<td>Fluctuation of quantity</td>
<td>1. Impact of regional CPO production yield such as harsh weather, diseases, seasonality yield etc.</td>
<td>1. Major impact to process, potential process shutdown.</td>
<td>1. Storage system of CPO for consistent supply to refinery and downstream processes.</td>
<td>15. Improvement of CPO production forecast for better supply chain and storage management.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Inconsistent supply from various suppliers, especially SMEs.</td>
<td>1. Potential shutdown of milling process during low resource of fruit bunches resulting higher cost for starting-up and shutting down the process.</td>
<td>1. Storage system of CPO for consistent supply to refinery and downstream processes.</td>
<td>16. Incorporate smart contract to increase the selling price of fresh palm fruit for SMEs with consistent supply.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Less impact to refinery and downstream processes due CPO has relatively longer shelf life compared to fruit bunches to allow storage for smooth supply.</td>
<td></td>
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</tr>
<tr>
<td>2. Inconsistency of quality</td>
<td>1. Different physical and chemical properties of CPO from different suppliers.</td>
<td>1. Potential product off-spec, however this is very unlikely due to establishment of adequate pretreatment processes.</td>
<td></td>
<td>Previous Recommendations 9 and 10 are applicable here:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Different sustainability profile from different suppliers due to different farming, harvesting practices</td>
<td>1. Potential unable to achieve MSPO requirement if the source has high environmental impact.</td>
<td></td>
<td>9. Blockchain technology to enhance traceability of products across the supply chain.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10. Cloud computing to optimise supply chain network from multiple sources, while all the required quantity, properties, and sustainability profile are achieved.</td>
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</tr>
<tr>
<td>3. Storage</td>
<td>Prolonged storage of CPO prior processing to downstream product.</td>
<td>1. Potential off-spec of CPO affecting efficiency of downstream processes, however this is considered as unlikely event due to CPO is relatively stable for storage.</td>
<td>1. Monitoring and control of storage condition.</td>
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<td>2. Various studies for optimum palm oil storage has been conducted.</td>
<td></td>
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<tr>
<td>4. Various suppliers</td>
<td>Involvement of multiple suppliers, especially from SMEs.</td>
<td>1. Potential inconsistency of raw material quality, which has same consequences as “inconsistency in quality” in Node 2.</td>
<td></td>
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</tr>
<tr>
<td>2. Processing efficiency</td>
<td>Monitoring of process</td>
<td>1. Visual inspection and monitoring of process condition.</td>
<td>1. Localise inspection which may cause potential exposure of hazardous environment to personnel.</td>
<td>1. Provide adequate protection such as personnel protective equipment when conduct routine monitoring at hazardous area.</td>
<td>17. Incorporation of IoT devices in the process to enable remote monitoring and access for process control.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Visual inspection may not able to detect process deviation accurately.</td>
<td>2. Process monitoring and control in control room.</td>
<td>Previous Recommendation 7 is applicable here:</td>
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<tr>
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<td>7. Incorporate IoT and big data analysis on machinery, detectors, controllers to determine optimum repair schedule prior to breakdown.</td>
</tr>
<tr>
<td>2. Process intervention/ control</td>
<td>Localised process control for each control loop.</td>
<td>1. Potential cascade effect from single control failure which may affects multiple process equipment and possible process shutdown.</td>
<td>1. Mitigation control system for cascade effect, such as sequential unit shutdown due to process deviation.</td>
<td>Previous Recommendation 17 is applicable here:</td>
<td></td>
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<tr>
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<td></td>
<td>17. Incorporation of IoT devices in the process to enable remote monitoring and access for process control.</td>
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<td></td>
<td>18. Incorporation of big data analysis, cloud computing and IoT to enable communication between multiple control loop/system for mitigation action upon any control loop failure.</td>
</tr>
<tr>
<td>3. Maintenance</td>
<td>Unplanned process shutdown due to equipment breakdown.</td>
<td>1. Frequent unplanned shutdown cause loss of production and potential equipment damage.</td>
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<td>Previous Recommendation 7 is applicable here:</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>7. Incorporate IoT and big data analysis on machinery, detectors, controllers to determine</td>
<td>(continued on next page)</td>
</tr>
</tbody>
</table>
Table A.2 (continued)

<table>
<thead>
<tr>
<th>Node 2</th>
<th>Description: Processes of palm oil including refinery, bio-diesel production, and food/pharmaceutical production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deviation</td>
</tr>
<tr>
<td>3.</td>
<td>1. Fluctuation of quantity</td>
</tr>
<tr>
<td>3.</td>
<td>1. Inconsistency of quality</td>
</tr>
<tr>
<td>3.</td>
<td>1. Over-storage of product in warehouse.</td>
</tr>
<tr>
<td>4.</td>
<td>1. Complex logistic problem such as traffic condition, weather, scheduling, etc.</td>
</tr>
<tr>
<td>4.</td>
<td>1. Fluctuation of feed cost</td>
</tr>
<tr>
<td>4.</td>
<td>1. Increase of CPO and processing cost in refinery.</td>
</tr>
<tr>
<td>5.</td>
<td>1. Traceability of resources</td>
</tr>
<tr>
<td>5.</td>
<td>2. Information security</td>
</tr>
</tbody>
</table>
Table A.3

HAZOP worksheet for Node 3

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Guideword</th>
<th>Causes</th>
<th>Consequences</th>
<th>Safeguards</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Feed</td>
<td>Fluctuation of quantity</td>
<td>1. Less production from process plant due to resources deficiency and unable to supply to downstream market/consumers.</td>
<td>1. Potential supply less than demand resulting temporary increase of product price. 2. Prolonged insufficient product for market may loss consumers interest and trust, eventually less demand. 3. May encourage development of new product or replaced by alternative source which affects overall palm oil market.</td>
<td>1. Palm oil is one of the highest yield oil crops, with multiple source from Malaysia, Indonesia and other countries with good security in supply chain. Thus, major deficiency of resources from multiple sources is unlikely to happen.</td>
<td>Previous Recommendation 21 is applicable here: 1. Big data analysis to forecast market demand for each downstream product to plan production strategy in advance.</td>
</tr>
<tr>
<td>2. Over production surpassing market demand.</td>
<td>1. Oversupply of product resulting in potential price reduction of downstream product, treated palm oil and CPO, which possible affects upstream processes, especially to SMEs in plantation.</td>
<td>1. Contract based supply chain system to ensure a minimum transaction between stakeholders. 2. Current demand for palm oil is relatively higher than the supply capability, especially in food and chemicals.</td>
<td>1. Proper labeling of expiry date of each palm oil product on packaging. 2. Treated and processed palm oil product usually has relatively long shelf life. Thus, no significant impact.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Inconsistency of quality</td>
<td>1. Unlikely to happened considering proper quality assurance and checking in the refinery and process plants.</td>
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</tr>
<tr>
<td>3. Storage</td>
<td>1. Over storage of downstream product.</td>
<td>1. Prolonged storage of palm oil product resulting in product storage time exceeded shelf life.</td>
<td>1. Periodic stock count. 2. Stock management system, such as replenish high demand product more frequently and reduce order amount for short expiry date product.</td>
<td>23. IoT and image processing devices to keep track of stock amount daily.</td>
<td></td>
</tr>
<tr>
<td>4. Various suppliers</td>
<td>1. Not applicable assuming each brand of product is unique and coming from dedicated process plant/company.</td>
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</tr>
<tr>
<td>2. Processing efficiency</td>
<td>1. Monitoring of process</td>
<td>1. Localised monitoring of product flow/sales in respective market/retailer to plan for stock replenishment.</td>
<td>1. Manual and localised monitoring of product sales and quantity may overlook the timeline for stock replenishment resulting temporary shortage of stock. 2. Process plant/supplier may not able to provide immediate supply for short notice order resulting product shortage in market.</td>
<td>1. Unlikely event for sudden increase of demand. 2. Forecasting technique was used to estimate the demand, such as bio-diesel.</td>
<td>Previous Recommendation 21 is applicable here: 1. Big data analysis to forecast market demand for each downstream product to plan production strategy in advance.</td>
</tr>
<tr>
<td>2. Process intervention/control</td>
<td>Not applicable for end users/consumers</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>3. Maintenance</td>
<td>Not applicable for end users/consumers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Product</td>
<td>1. Fluctuation of quantity</td>
<td>1. Increasing market demand.</td>
<td>1. Rapid increase of market demand leading to insufficient supply of product, resulting insecure supply capability to end users/customers.</td>
<td>1. Unlikely event for sudden increase of demand. 2. Forecasting technique was used to estimate the demand, such as bio-diesel.</td>
<td>Previous Recommendation 21 is applicable here: 1. Big data analysis to forecast market demand for each downstream product to plan production strategy in advance.</td>
</tr>
<tr>
<td></td>
<td>2. Decreasing market demand.</td>
<td>1. Lack of demand resulting oversupply of palm oil product leading to price drop, possible impact to palm oil processing company and upstream processes. 2. Refer to consequences in “Fluctuation of quantity” in Node 3</td>
<td></td>
<td></td>
<td>Previous Recommendation 21 is applicable here: 1. Big data analysis to forecast market demand for each downstream product to plan production strategy in advance.</td>
</tr>
<tr>
<td>2. Inconsistency of quality</td>
<td>Unlikely to happened considering proper quality</td>
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</tbody>
</table>

(continued on next page)
Table A.3 (continued)

<table>
<thead>
<tr>
<th>Node 3</th>
<th>Description</th>
<th>Market for products/end users for palm oil product including palm bio-diesel, edible palm oil and palm chemicals products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deviation</td>
<td>Guideword</td>
<td>Causes</td>
</tr>
<tr>
<td>1. Traceability of resources</td>
<td>Not applicable</td>
<td>1. Unable to trace the source of product due to the complex supply chain from plantation to end users, such as Halal certification for food or sustainability profile/performance.</td>
</tr>
<tr>
<td>2. Information security</td>
<td>Not applicable</td>
<td>1. Unable to trace each batch of product with respect to different batch of resources.</td>
</tr>
<tr>
<td>3. Storage</td>
<td>Not applicable</td>
<td></td>
</tr>
<tr>
<td>4. Product distribution</td>
<td>Not applicable</td>
<td></td>
</tr>
<tr>
<td>4. Cost</td>
<td>Fluctuation of feed cost</td>
<td>Same caused identified as “Fluctuation of product price” in Node 2 and applicable here.</td>
</tr>
<tr>
<td>5. Accuracy of information</td>
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</tbody>
</table>
| Acknowledgement

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References


