INTEGRATION OF INTERNET OF THINGS AND MACHINE LEARNING FOR LOGISTICS 4.0 OF FRESH MANGO AGROINDUSTRY

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SUMMARY

SARI INTAN KAILAKU. Integration of Internet of Things and Machine Learning for Logistics 4.0 of Fresh Mango Agroindustry. Supervised by YANDRA ARKEMAN, Y ARIS PURWANTO, and FAQIH UDIN.

Agroindustry serves as a vital economic driver by connecting farming, fresh handling and processing industries, and end consumers through an interconnected value chain. The advancements in agroindustrial engineering have expanded markets, thereby amplifying the logistics activities. However, maintaining the quality of perishable goods, like fresh fruit, during long-distance transportation remains a significant challenge in Indonesia due to inadequate postharvest handling and transportation conditions.

Mangoes, a key horticultural product in Indonesia, are traded both domestically and internationally. Enhancing the quality assurance of these mangoes is crucial for increasing their market competitiveness. Real-time quality monitoring using Information and Communication Technology (ICT) and Internet of Things (IoT) has been identified as a solution to this issue. Moreover, machine learning can predict product quality and provide critical data for stakeholders to make informed logistics and quality-related decisions. The integration of IoT and machine learning can develop an accurate real-time quality monitoring system, boosting the competitiveness of Indonesia's mango industry and reducing postharvest losses.

This study aims to integrate IoT architecture with machine learning techniques to develop an intelligent system for the long-distance transportation of fresh mangoes, supporting the implementation of Logistics 4.0. The specific objectives are: (1) to investigate the respiration pattern and quality characteristics of mangoes during storage, (2) to model and classify mango maturity based on quality characteristics affected by storage conditions and duration, (3) to develop machine learning model for mango maturity prediction, (4) to create IoT architecture for real-time monitoring of long-distance mango transportation, and (5) to design an IoT-based information system for mango transportation. The proposed solutions include developing real-time monitoring of transportation conditions and real-time maturity prediction. This involves creating an information system, machine learning algorithms, IoT architecture and device, along with a model for maturity changes. Machine learning algorithm, IoT device, and information system's performances were measured to ensure scalability.

The research begins with system identification, followed by simultaneous modeling of maturity levels, IoT device engineering, and application development. A Deep Learning model is trained using datasets from laboratory observations of mango quality changes during storage and IoT-monitored environmental conditions. Transportation simulations validate the system's performance in both land and inter-island transportation.

Findings indicate that mangoes with 85% maturity are optimal for long-distance transportation. A classification model for mango maturity based on quality attributes is developed. This model, utilizing changes in physicochemical parameters during storage, achieves over 95% accuracy in predicting maturity level changes during transportation.

IoT devices successfully collect, record, and transfer transportation data to the database and information system. The information system provides accessible transportation information and maturity predictions to stakeholders via a web-based application.

This dissertation exemplifies a compelling Artificial Intelligence of Things (AIoT) use case by integrating IoT architecture with machine learning techniques to tackle the logistics and transportation challenges of perishable goods. The IoT component involves sensors and devices that monitor environmental conditions, collecting real-time data transmitted to a central database. Machine learning models then analyze this data to predict mango maturity and quality changes during transportation, providing timely alerts to stakeholders for informed decision-making. This AIoT integration not only enhances quality monitoring accuracy but also optimizes the supply chain, reducing postharvest losses and improving market competitiveness. The project's success highlights the transformative potential of AIoT in revolutionizing traditional agroindustries and driving sustainable economic growth.

The implications of this study are significant for the agriculture sector, particularly in enhancing logistics performance and product quality assurance. Accurate prediction of agricultural product maturity levels can revolutionize logistics and inventory management by optimizing distribution, thus reducing losses. Future research should focus on improving predictive models by incorporating additional factors, exploring the effects of varying storage conditions, and expanding the dataset to include a wider range of fruit varieties. Real-time predictive analytics present a promising opportunity to enhance the agricultural value chain. The system's autonomy can be improved by integrating actuators to manage environmental conditions dynamically, and by developing advanced IoT architectures that include robust, scalable systems with high-precision sensors for comprehensive real-time monitoring. The incorporation of intelligent decision-making applications will further optimize logistics processes and resource management. Additionally, adopting blockchain technology could revolutionize the mango supply chain by ensuring traceability and transparency, thus improving quality assurance and stakeholder trust. Establishing standardized data formats and improving machine learning algorithms will enhance the system's efficiency and adaptability, making it a model for sustainable practices in agricultural logistics.

RINGKASAN

SARI INTAN KAILAKU. Integrasi *Internet of Things* dan *Machine Learning* untuk Logistik 4.0 pada Agroindustri Mangga Segar. Dibimbing oleh YANDRA ARKEMAN, Y ARIS PURWANTO, and FAQIH UDIN.

Agroindustri berfungsi sebagai penggerak perekonomian yang penting dengan menghubungkan pertanian, industri pengolahan dan penanganan segar, serta konsumen akhir melalui rantai nilai yang saling berkaitan. Kemajuan dalam teknik agroindustri telah memperluas pasar, sehingga memperkuat kegiatan logistik. Namun, menjaga kualitas produk yang mudah rusak, seperti buah segar, selama pengangkutan jarak jauh masih menjadi tantangan besar di Indonesia karena kondisi penanganan dan pengangkutan pascapanen yang tidak memadai.

Mangga, salah satu produk hortikultura utama di Indonesia, diperdagangkan baik di dalam negeri maupun internasional. Meningkatkan jaminan mutu mangga sangat penting untuk meningkatkan daya saing pasar. Pemantauan mutu secara *real-time* menggunakan Teknologi Informasi dan Komunikasi (TIK) dan *Internet of Things* (IoT) merupakan solusi untuk masalah ini. Selain itu, *machine learning* dapat memprediksi mutu produk dan menyediakan data penting bagi pemangku kepentingan untuk membuat keputusan logistik yang tepat. Integrasi IoT dan *machine learning* dapat mengembangkan sistem pemantauan mutu yang akurat secara *real-time*, meningkatkan daya saing industri mangga Indonesia, dan mengurangi kerugian pascapanen.

Penelitian ini bertujuan untuk mengintegrasikan arsitektur IoT dengan teknik *machine learning* untuk mengembangkan sistem cerdas transportasi jarak jauh buah mangga segar, mendukung implementasi Logistics 4.0. Tujuan spesifik penelitian antara lain: (1) mengetahui pola respirasi dan karakteristik mutu mangga selama penyimpanan, (2) memodelkan dan mengklasifikasikan kematangan mangga berdasarkan karakteristik mutu yang dipengaruhi oleh kondisi dan durasi penyimpanan, (3) mengembangkan model *machine learning* untuk prediksi kematangan mangga, (4) membangun arsitektur IoT untuk monitoring transportasi mangga jarak jauh secara *real-time*, dan (5) merancang sistem informasi transportasi mangga berbasis IoT. Solusi yang diusulkan mencakup pengembangan pemantauan kondisi transportasi secara *real-time* dan prediksi kematangan secara *real-time*. Hal ini melibatkan pengembangan sistem informasi, algoritma *machine learning*, arsitektur dan perangkat IoT, serta model untuk perubahan kematangan. Kinerja algoritma *machine learning*, perangkat IoT, dan sistem informasi diukur untuk memastikan skalabilitasnya.

Penelitian diawali dengan identifikasi sistem, dilanjutkan dengan pemodelan tingkat kematangan secara simultan, rekayasa perangkat IoT, dan pengembangan aplikasi. Model *Deep Learning* dilatih menggunakan kumpulan data dari pengamatan laboratorium terhadap perubahan mutu mangga selama penyimpanan dan kondisi lingkungan yang dipantau oleh IoT. Simulasi transportasi memvalidasi kinerja sistem baik pada transportasi darat maupun antar pulau.

Temuan penelitian menunjukkan bahwa mangga dengan kematangan 85% optimal untuk transportasi jarak jauh. Model klasifikasi kematangan mangga berdasarkan atribut mutu telah dikembangkan. Model ini, dengan memanfaatkan

perubahan parameter fisikokimia selama penyimpanan, mencapai akurasi lebih dari 95% dalam memprediksi perubahan tingkat kematangan selama transportasi.

Perangkat IoT berhasil mengumpulkan, mencatat, dan mentransfer data transportasi ke database dan sistem informasi. Sistem informasi menyediakan informasi transportasi dan prediksi kematangan yang dapat diakses oleh pemangku kepentingan melalui aplikasi berbasis web.

Disertasi ini memberikan contoh kasus penggunaan *Artificial Intelligence of Things* (AIoT) yang menarik dengan mengintegrasikan arsitektur IoT dengan teknik *machine learning* untuk mengatasi tantangan logistik dan transportasi barang yang mudah rusak. Komponen IoT melibatkan sensor dan perangkat yang memantau kondisi lingkungan, mengumpulkan data *real-time* yang dikirimkan ke database pusat. Model *machine learning* kemudian menganalisis data tersebut untuk memprediksi kematangan mangga dan perubahan mutu selama pengangkutan, sehingga memberikan peringatan *real-time* kepada pemangku kepentingan untuk pengambilan keputusan yang tepat. Integrasi AIoT ini tidak hanya meningkatkan akurasi pemantauan mutu tetapi juga mengoptimalkan rantai pasok, mengurangi kerugian pascapanen, dan meningkatkan daya saing pasar. Keberhasilan penelitian ini menggarisbawahi potensi transformatif AIoT dalam merevolusi agroindustri tradisional dan mendorong pertumbuhan ekonomi berkelanjutan.

Implikasi dari studi ini sangat signifikan terhadap sektor pertanian, khususnya dalam meningkatkan kinerja logistik dan jaminan mutu produk. Prediksi tingkat kematangan produk pertanian yang akurat dapat merevolusi logistik dan manajemen inventaris dengan mengoptimalkan distribusi, sehingga mengurangi kerugian. Penelitian di masa depan perlu berfokus pada peningkatan model prediktif dengan memasukkan faktor-faktor tambahan, mengeksplorasi dampak dari berbagai kondisi penyimpanan, dan memperluas kumpulan data untuk mencakup lebih banyak varietas buah. Analisis prediktif *real-time* menghadirkan peluang menjanjikan untuk meningkatkan rantai nilai pertanian. Otonomi sistem dapat ditingkatkan dengan mengintegrasikan aktuator untuk mengelola kondisi lingkungan secara dinamis, dan dengan mengembangkan arsitektur IoT canggih yang mencakup sistem yang kuat dan dapat diskalagandakan dengan sensor presisi tinggi untuk pemantauan *real-time* yang komprehensif. Penggabungan aplikasi pengambilan keputusan cerdas akan lebih mengoptimalkan proses logistik dan manajemen sumber daya. Selain itu, penerapan teknologi blockchain dapat merevolusi rantai pasok mangga dengan memastikan ketertelusuran dan transparansi, sehingga meningkatkan jaminan mutu dan kepercayaan pemangku kepentingan. Selain itu, perlu penetapan format data standar dan penyempurnaan algoritma *machine learning* akan meningkatkan efisiensi dan kemampuan sistem untuk beradaptasi, menjadikannya sebuah model untuk logistik pertanian berkelanjutan.

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PREFACE

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Hopefully, this dissertation will be valuable for the community and the advancement of science.

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Sari Intan Kailaku

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