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Review

Haystack Fires in Australia: Causes and Considerations for Preventative Management

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Abstract: The spontaneous combustion of hay when stacked after baling is an issue frequently encountered by farmers in Australia and elsewhere. While there is a basic understanding of why this occurs the interactions of the many factors involved mean that there is still no consistent methodology for its prevention. Recent technological advances in sensors and communications allow for the continual collection of quantitative data from hay bales or stacks for managers to utilize in their decision-making processes with regards to minimizing the risks of spontaneous combustion. This review discusses both the factors involved in the spontaneous combustion of haystacks and the types of sensors available for the monitoring of these factors. This includes advancements in sensor technologies and their practical applications in monitoring hay bale conditions.

Keywords: spontaneous combustion; high temperature; remote sensing

1. Introduction

The phenomenon of spontaneous combustion has long been recognised since ancient times and is reviewed in the seminal paper by Browne [1]. Pliny the Elder wrote of spontaneous combustion in his *Naturalis Histotæ* published in 77 AD [2]. Historical accounts, like that of Pliny the Elder's, underscore the long-standing awareness of the level of risk in agriculture of spontaneous combustion.

"When the grass is cut it should be turned towards the sun and must never be stacked until it is quite dry. If this last precaution is not carefully taken, a kind of vapor will be seen arising from the rick in the morning, and as soon as the sun is up it will ignite to a certainty and so be consumed".

A variety of definitions of the term spontaneous combustion have been suggested in the literature. This paper will use the definition by DiNenno et al. [3] as "the general phenomenon of an unstable (usually oxidizable) material reacting with the evolution of heat, which to a considerable extent is retained inside the material itself by virtue of either poor thermal conductivity of the material or its container". A primary component of the ability of a material to spontaneously combust is its ability to self-heat. Self-heating may be defined as an increase in temperature due to exothermicity of internal reactions [4].

According to the *Fire Protection Handbook*, self-heating or spontaneous heating is the process whereby a material increases in temperature without drawing heat from its surroundings [5]. This phenomenon is highly exothermic in nature. It involves the rapid generation and accumulation of heat through biological and chemical processes, characterized as self-heating of stored solid and liquid materials, without heat absorption from external sources. This continues until the material reaches its ignition point, resulting in spontaneous combustion. There are many intricacies of spontaneous combustion and its ability to cause the ignition of a wide variety of materials including porous, organic materials.

Many common organic materials are susceptible to typical biological and chemical type spontaneous combustion processes. These include hay, straw, grains, green plants,

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peat, bituminous coal, lignite coal, animal fat, vegetable fat, rapeseed, oil plants, seeds, plant waste, animal feces (manure) and cellulose pulp, etc. This paper primarily focuses on the facts and considerations of the spontaneous combustion of hay. Over the years, many post-fire investigations have shown that experts were unable to correctly identify the causes of fire. This is due to a lack of studies and publications on spontaneous combustion and limited knowledge in thermodynamics, chemistry, biology and physics [6]. Surprisingly, the spontaneous combustion of hay is not yet fully understood by agricultural producers and warrants a more comprehensive investigation.

The spontaneous combustion of hay products in Australia poses a significant economic and health risk for the producer. The value of pasture (including lucerne), cereal, and other crops cut for hay in Australia exceeded AUD 2.5 billion in 2020 (Figure 1). The ability of producers to safely store and manage their fodder usage is curtailed by the complex nature by which it degrades. Spontaneous combustion in freshly baled hay is a frequently encountered problem with hay production. In Australia between 2019 and 2022 the Insurance Australia Group received 60 insurance claims valued at AUD 2.6 million that were attributed to the spontaneous combustion of hay. It has been established that the interaction between moisture and sugar content is an important determiner of hay self-heating. Additionally, other factors of spontaneous combustion such as bale size, bale type, environmental conditions and storage conditions are reviewed. The two phases of spontaneous combustion are also examined to provide leads for the best management practices.

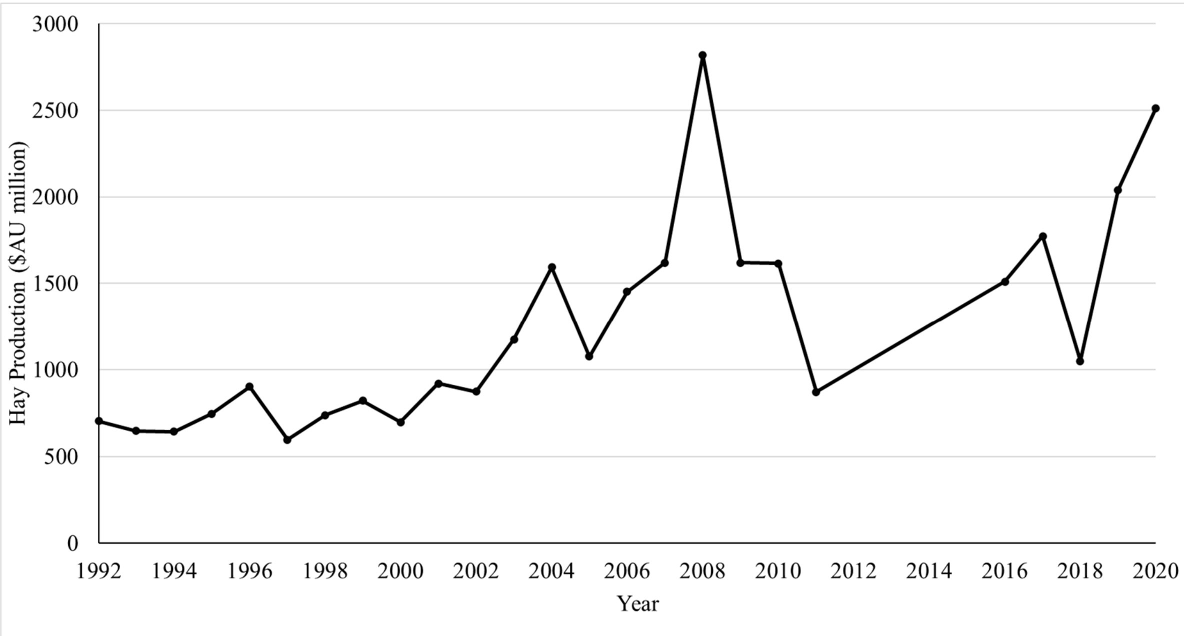

Figure 1. The value of hay production in Australia between 1992 and 2020 [7].

Finally, we introduce the utilisation of 'smart agriculture' to streamline the management of hay susceptible to degradation through spontaneous combustion. The use of the Internet of Things (IoT), sensors and communication devices is also discussed. Additionally, the requirement of smart agriculture to be secure and private is investigated.

2. Spontaneous Heating and Combustion

The heating process of a haystack is the result of various chemical and biological reactions, which are generally "exothermic" in nature. The oxidation of the hay generates heat, which is regulated by the quantity of the reactants, the insulation capacity of the hay to contain the heat generated itself, and time [8]. Self-heating or spontaneous heating is entirely responsible for the spontaneous combustion of haystacks and occurs regardless of bale size and shape. This process is expected to be slow, and if the heat generated cannot be dissipated it will continue to build up to ignition resulting in spontaneous combustion [9]. If the rate of heat dissipation is higher than the rate of heat generation, the hay will eventually cool down and ignition will not take place.

Spontaneous heating may be defined as the most obvious consequence of plant and microbial respiration where plant cells and different microorganisms utilise sugars in the presence of oxygen to produce carbon dioxide, water and heat [10].

This process increases the internal bulk temperature of the hay bale because of slow oxidation without the involvement of any external heat sources [11]. This in turn promotes the drying process through evaporation, resulting in dry matter loss [12], alteration in fibre components [13], protein content [14] and calculated energy content [15]. Several factors are responsible for the generation and extent of spontaneous heating in hay bales. These include (i) bale size, (ii) bale density, (iii) environmental conditions, (iv) moisture content, (v) use of additives and preservatives and (vi) storage conditions. Generally, the degree of heating in a hay bale is considered a quality indicator for the understanding of possible alterations in nutritive value under storage.

3. Factors Responsible for the Spontaneous Heating of Haystacks

3.1. Bale Size

The possibility of spontaneous combustion increases with the size of the body material in thermal contact [9]. For larger bales, it will be difficult for the material to dissipate heat generated by the self-heating process. The heat dissipation capacity of hay is linked with surface-core distance, which is applicable to both individual bales and haystacks. Higher density, large sized bales are at greater risk of high core temperatures compared with the small rectangular bales [16] and require reduced threshold moisture concentrations for baling [17] and storage [14]. Large round bales can also exhibit extensive spontaneous heating, such as heating degree days (HDD) > 300 °C or maximum internal bale temperature, compared to small rectangular hay bales [12]. Martinson et al. [18] reported that large round bales of *Dactylis glomerata* (1.2×1.5 m^2) were prone to significant mould attack followed by heating and quality losses, even at lower moisture concentrations. This does not imply that small rectangular bales are not at risk of self-heating, which primarily depends on the heat generated after storage at the centre of the stack. Generally, self-heating occurs when hay bales are stored at >20% moisture content with 5–10% loss in dry matter [19]. Generally, the rule of thumb for maintaining acceptable moisture contents of haystacks in storage is 20% or less. Small rectangular sized bales can be stored safely baled at 18–20% moisture content. But the same hay as large round or rectangular bales should not contain higher than 16–18% moisture.

3.2. Bale Density

Bale density influences the potential for spontaneous heating in the haystack. However, it is very difficult to maintain bale density with field scale farm equipment due to crude machine adjustments [20]. But the laboratory-scale baling system proposed by Coblentz et al. [21] allows accurate and precise control on bale density at the experimental level. Bale density is greatly influenced by the tightness of wrap or bale compression, which is variable depending on operator preference and the equipment being used. Coblentz et al. [22] reported that conventional rectangular bales of *Cynodon dactylon* hay packed at high and medium bale densities (overall mean 208 and 186 kg/m^3) had no significant difference on spontaneous heating when stored at various moisture concentrations ranging from 18 to 33%. However, increased density of round bales showed significant heat damage compared with rectangular bales within the same moisture range [23].

To minimize the labour and transport cost, hay producers have increased the use of baling equipment to make larger, higher-density hay bales which may result in poor microbial respiration during storage [20], as bale density has been identified to have a positive influence on spontaneous heating [24]. The increase in spontaneous heating in response to increased bale density is primarily due to the compaction or tightness by packing comparatively higher dry matter into the bale [25,26]. Montgomery et al. [27] reported that the mean temperature at the centre of round bales (average weight 624 kg) reached approximately 90 °C compared with 40 °C in 25 conventional rectangular haystacks from the same forage.

3.3. Environmental Conditions

Ambient temperature and air movement play a crucial role in the heat accumulation process through heat dissipation from the stored hay material. Generally, higher ambient temperatures lessen the chances of cooling by air. Air movement helps in eliminating evaporated moisture and accumulated heat around the stack. Heat accumulation during storage mainly depends on ambient temperature, air movement and relative humidity [16].

At a given temperature when relative humidity is high, hay requires more time to dry compared with lower humidity. High ambient temperatures are favourable to the accelerated bacterial and fungal activity which are mainly responsible for self-heating [28]. High ambient temperatures also reduce the chances of losing energy to the neighbouring atmosphere. Thus, higher ambient temperatures and poor air movement may contribute to the favourable conditions for accelerated microbial activity followed by heat generation and accumulation, making the haystack prone to spontaneous heating.

3.4. Moisture Content

Moisture content during baling is the most important factor that influences excessive heating, resulting in spontaneous ignition. Hay that is baled above the recommended levels of moisture content is susceptible to spontaneous heating where plant sugars are respired into carbon dioxide, water and heat [26]. According to Bass et al. [29], increased bale moisture content usually results in increased bale temperature in storage.

Generally, hay from the current season, even under optimum conditions, is at greater risk as water activity increases during spring since most storage sugars responsible for heat production have been left unused. Baling lucerne (*Medicago sativa*) at higher moisture contents (>15%) reduces leaf losses during mechanical handling and field curing time; however, moisture content should be below this level for storage. The upper limit of moisture for large round lucerne bales is about 18–20%. Hay baled at greater than 20% moisture content will usually increase storage losses by over 24% [30] as a consequence of the oxidative reaction of spoilage microbes. Table 1 shows the safe moisture contents for storage of various bale types.

Table 1. Recommended moisture contents (%) for safe storage of various bale types.

Bale Type	Moisture Content (%)
Small rectangular bales	16–18
Round bales (Soft centre)	14–16
Round bales (Hard centre)	13–15
Large rectangular bales	12–14
Export hay	<12

Coblentz et al. [22] showed that hay baled with the highest moisture concentration exhibited more intense and prolonged heating than drier hay (Table 2). Interestingly the material baled had no influence on this; the pattern of spontaneous heating for bermudagrass was similar to lucerne hay. Bales continued to lose moisture until they reached 12–15% during storage. The final moisture concentration depended upon the environmental and storage conditions.

The interface between dry and wet hay is ideal for spontaneous combustion due to the presence of optimal heat, dampness and insulation. The green or high moisture region within a bale or stack expands as the water produced through plant and microbial respiration becomes trapped in this area and gradually spreads to the surrounding vicinity. However, combustion can be prevented if the generated heat dissipates anyway.

Higher moisture content during storage is highly conducive to rapid microbial growth and development, which in turn results in increased respiration [31] followed by heat generation.

Table 2. Effect of moisture contents of hay on storage temperature, adapted from Coblentz et al. [22].

	Temperature during Storage (°C)			
Moisture (%)	**Maximum**	**Minimum**	**Average (30 Day)**	**Average (60 Day)**
32.50	61.78	31.39	45.50	39.78
28.70	59.50	31.11	45.28	39.72
24.80	54.22	30.28	42.28	37.89
20.80	43.50	30.11	37.72	35.39
17.80	40.22	30.00	35.89	34.28

To better understand the magnitude and duration of heating in hay bales, the heating degree day (HDD) concept is often used as a response variable in hay preservation studies. An HDD > 30 °C represents the summations of the daily increment by which the internal bale temperature was greater than 30 °C [12]. Thus, total HDD during storage serves as a single numeric response variable that integrates both the intensity and duration of spontaneous heating within each bale. Figure 2 represents data from several lucerne hay experiments revealing a positive linear relationship between moisture content and HDD (r^2 = 0.902) for lucerne-orchardgrass hays packaged in 0.90 and 1.20 m diameter round bales [10]. It is evident that moisture content is the primary variable causing spontaneous heating within any given bale. Later, when bale diameter was increased to 1.50 m, the positive linear relationship between moisture content and HDD remained consistent, but the HDD response was accelerated with per unit of moisture content [12].

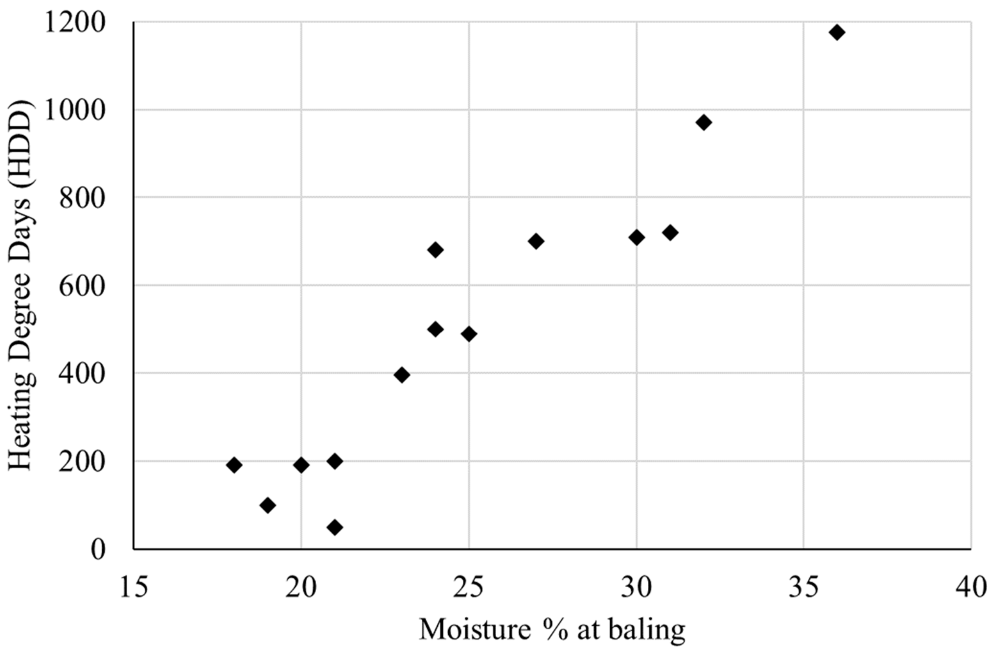

Figure 2. Relationship between heating degree days > 30 °C and moisture content at baling, adapted from Coblentz et al. [10].

3.5. Storage Conditions

The respiration process occurring in both plant cells and micro-organisms is responsible for the initial increase in internal bale temperature immediately after baling [32]. This results in spontaneous heat generation which often lasts approximately five days. Later, the internal bale temperature may decrease for a short period of time followed by the initiation of an extended period of heating lasting for several weeks [10]. This prolonged period of heating occurs due to increased microbial respiration in their rapid growth and development stage during bale storage.

In addition, hay baled at a high moisture content (30%) maintains a higher internal temperature compared to drier hay due to increased microbial respiration [33]. Dry hay does not heat excessively due to the absence of adequate moisture to support microbial growth. Figure 3 illustrates the typical pattern of heating and cooling that occurs over storage time for conventional rectangular bales of lucerne hay made at 20 and 30% moisture.

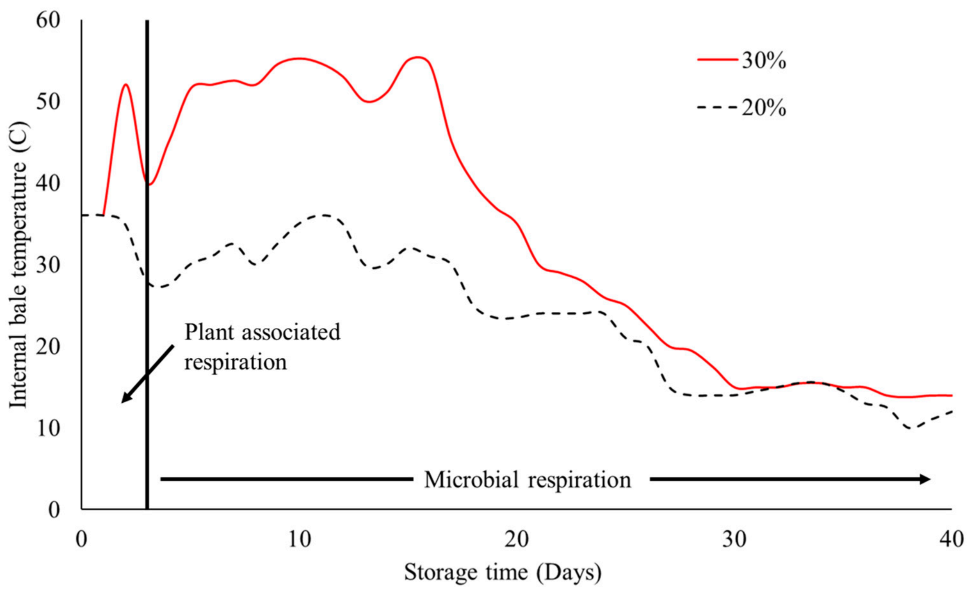

Figure 3. Patterns of heating in lucerne hay baled at 20 and 30% moisture during storage, adapted from Coblentz et al. [34].

3.6. Use of Additives and Preservatives

During hay production, field losses can be minimized by baling at higher moisture concentrations, i.e., between 20 and 25%. However, when hay is baled above 15–10% moisture content rapid microbial activity may influence hay quality, nutritive value and dry matter loss [12,35]. Hence, preservatives are used to counter microbial interference and allow baling above 20% moisture contents. While these preservatives are effective, their long-term environmental impact, particularly regarding greenhouse gas emissions, soil health and microbial balance, needs further investigation.

Common preservatives used for wet hay are organic acids, anhydrous ammonia and bacterial inoculants. Organic acids, mainly propionic acid based, are reported to inhibit growth of moulds, yeasts and bacteria for up to 6 months [36,37]. Buffered acid products are widely used as a replacement for strong acids to lessen corrosiveness [26]. Anhydrous ammonia is reported to be highly effective against mould development in hay when treated and wrapped in plastic, as both heating and dry matter losses are reduced in up to 35% moisture content [38,39]. Considering its effectiveness, the safety concerns to humans and to animals fed the forage deter the application of ammonia in hay preservation [40].

Apart from traditional chemical preservatives, limited information is available regarding the use of microbiological compounds in improving hay quality. Basically, bacterial inoculants developed to improve the fermentation of silage or hay have been ineffective in reducing storage temperatures in wet hay. Lactic acid preservatives containing *Lactobacillus acidophilus* failed to reduce bale temperature during storage [29]. According to both Deetz et al. [41] and Rotz [38], there were no significant effects on mould, colour, heating, dry matter loss or change in forage quality when hay was inoculated with strains of *Lactobacillus* as forage-stabilizing compounds. Rotz [38] also reported that although *Bacillus* bacteria were better suited to the aerobic hay environment, no significant storage improvements were observed.

4. Phases of Biochemical Spontaneous Combustion

It is obvious that there are various ongoing chemical and biological reactions that can generate heat in a material. The mystery of spontaneous combustion lies in these self-heating mechanisms occurring. However, time and exposure to elevated temperature are crucial for any candidate material to gain a temperature high enough so that it can smoulder [8]. For combustion to occur, the rate of heat generation must consistently exceed heat dissipation through conduction, convection and radiation. The overall process can be outlined as shown in Figure 4.

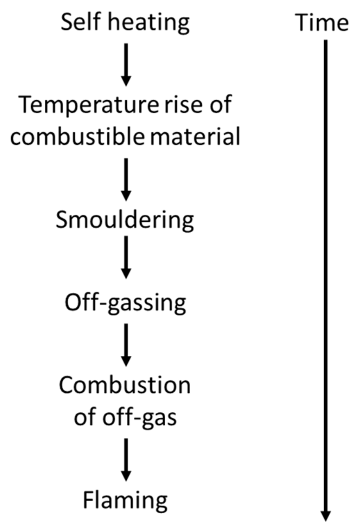

Figure 4. Schematic diagram of spontaneous combustion (adapted from Phillips [8]).

According to Dworakowski [6], spontaneous combustion of plant materials occur in two successive phases. The different phases of spontaneous combustion are outlined in Figure 5.

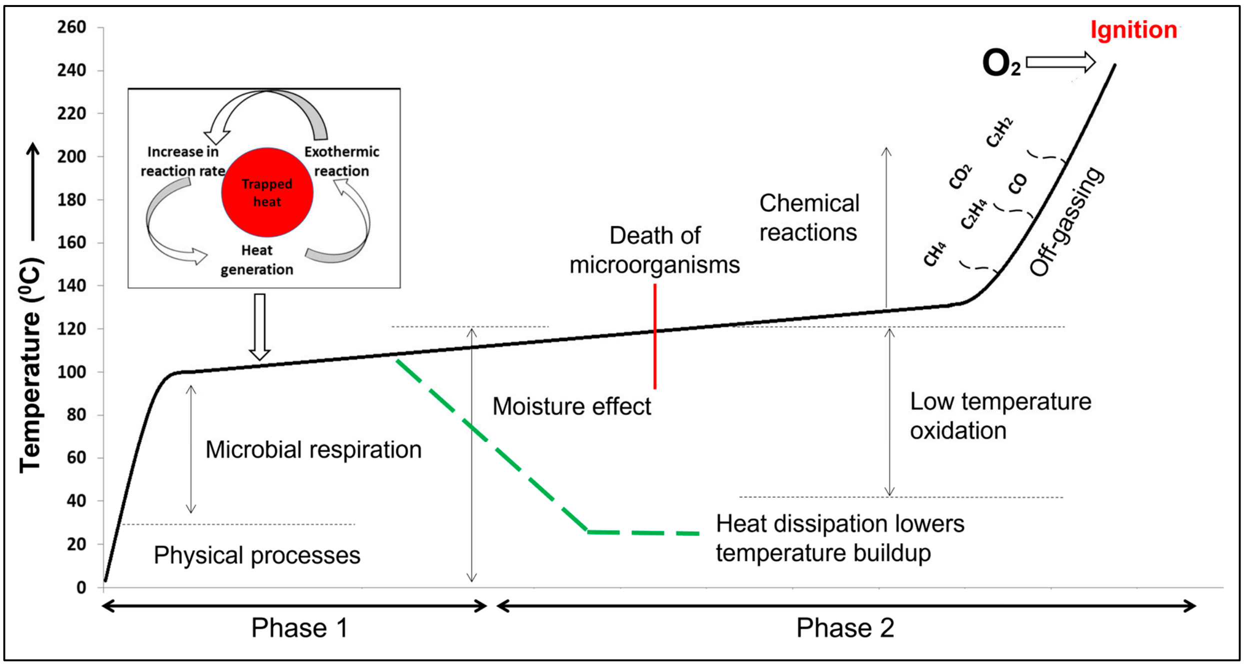

Figure 5. Different phases of spontaneous combustion in a haystack.

4.1. Phase 1

During the first phase of spontaneous combustion, microorganisms such as bacteria, fungi and yeasts grow rapidly with an increased level in respiration and oxygen absorption (Figure 5). The length of this respiration process depends on the quantity of thick stems and leaves containing large amounts of water. Since plant tissue and microorganisms use the same substrate during respiration, they possess similar effects on alterations of nutritive value of the plant material [42]. Respiration is a process that occurs in all plant cells and living cells of other organisms and is the reverse process to photosynthesis where photosynthesis products are absorbed during respiration [43].

During respiration, oxygen and other organic substances such as glucose are consumed which results in the generation of thermal energy. It is estimated that 1 g of glucose releases approximately 4 kcal of energy during decomposition [44].

As catalysts of chemical reactions, enzymes play a vital role in respiration, facilitating the generation of large amounts of thermal energy. During the initial phase, respiration is intensified when the temperature reaches between 20 and 35 °C, with mesophilic bacteria having the highest activity within this temperature range [45]. Such elevated temperature and moisture conditions are conducive to the rapid growth and development of microorganisms. Increasing microbial activity causes oxygen depletion, which in turn accelerates the decomposition and fermentation processes through the breakdown of complex substances into simpler compounds.

When hay temperature reaches approximately 37 °C or above, reactions occur wherein proteins and amino acids combine with plant sugars, forming brown polymer resembling lignin [19], that makes hay brownish in colour and mouldy in appearance. The browning of hay results in reduced digestibility of proteins, fibres and carbohydrates (Table 3). Subsequently, the heat produced by these reactions merges with heat produced from microbial growth causing increases in the temperature of the hay bale [19].

Table 3. Possible alterations of hay associated with temperature [46].

Temperature (°C)	Alterations Associated
46–52	Moulds and odours develop and decrease palatability when coupled with high moisture.
>49	Reduced digestibility of protein, fibre and carbohydrate compounds.
54–60	Hay is brown and very palatable because of the caramelization of sugars; unfortunately, nutritional value is reduced.
>66	Hay may turn black and spontaneous combustion is possible.

4.2. Phase 2

The anaerobic decomposition of carbohydrates and anaerobic enzymatic decomposition of proteins and amino acids is initiated during this phase (Figure 5).

Various plant materials have good insulating properties due to minimum heat loss. Thus, the temperature rises to 60–90 °C, which results in heat accumulation. Due to the increased temperature, plants lose moisture rapidly which leads to the pectin decomposition and the subsequent formation of formic acid (CH_2O_2), ammonia (NH_3) and acetic acid (CH_3COOH) and results in the formation of a foul odour [6]. Animal manure, hay, straw and damp grain are examples of typical plant materials that generally heat up to temperatures of 40–90 °C and above. Further decomposition of proteins takes place at temperatures between 90 and 100 °C. Hydrogen sulphide (H_2S) and Furfural ($C_5H_4O_2$) are formed later with the result that plant materials desiccate and agglomerate. At this stage, the intensity of chemical reactions increases; however, microbial activity decreases. At this elevated temperature (approximately 100 °C), microbial development is ceased due to death [47]. Water completely evaporates from the plant mass and the temperature continues to increase rapidly until the plant material becomes desiccated at a temperature of approximately 150 °C.

This stage may be regarded as the start of the dry distillation of the plant material. Dry distillation may be defined as the decomposition process of lignified plant materials with exposure to high temperature conditions having limited or no access to air [48]. Throughout this process, various compounds and gases (including methane, carbon dioxide, carbon monoxide, ethylene, acetylene, etc.) are formed and released that participate later in various complex reactions (Figure 5). Several factors influence the gas formation process including the critical temperature at which the decomposition takes place and the internal pressure of the stored material (bale or stack) [6]. The rate and intensity of the desiccation and decomposition process depends on the moisture content of the stored plant material while the effect of temperature mainly depends on the thickness and size of the stored plant material.

Considering the volume of the stored plant material and poor thermal conductivity, heat accumulates inside the stored plant stack due to poor dissipation. This results in a rapid temperature increase to 180 °C and above as the decomposition process becomes more intensive and faster. Additionally, the moisture content of the stored plant material influences the thermal process. Further decomposition of the plant material leads the temperature rise to 230–260 °C, which causes an increase in vapour pressure in the stack. Moreover, the accumulated heat inside the stack gets trapped due to low or minimal cooling and heat dissipation. The combustion of the generated gas take place at 250–260 °C with the formation of pyrophoric carbon, which has a great capacity to absorb oxygen from air [6]. Thus, the temperature increases further, and the carbon starts to smoulder which leads to the burning of fire channels toward the frontal, lateral or upper surface of the stack. The external surface of the stack sets fire after the burning of the fire channels. The intensity of the fire increases rapidly when the flame encounters oxygen present in the air leading to the rapid generation of a carbon monoxide cloud and methane.

5. Monitoring of Agricultural Parameters

Sensors and devices have been serving agriculture and farming sectors over the years by monitoring various environmental parameters and farm components. Comparing the effectiveness of different sensors, such as temperature, humidity and soil moisture sensors, in real-world farm settings could provide valuable insights for future technology development.

The invention of IoT (Internet of Things) has made a major revolution regarding the advancements of sensors at field level. The global sensors market has been expanding with an extraordinary growth worldwide of approximately USD 190 billion in 2021 as compared to 2011 (USD 62 billion), where environmental sensors account for more than 13% of the total amount [49]. In this context, a wide range of sensors and devices are currently available for environmental monitoring with various levels of complexities and functionalities, such as pH, temperature, soil moisture, humidity, ultraviolet and passive infrared (PIR), light, airflow, etc. However, temperature, humidity and soil moisture are considered the most critical environmental variables for smart farming practice [50]. Table 4 represents the most common sensors and devices used by IoT in the agricultural sector.

Table 4. Common sensors utilised by IoT systems used in agriculture.

Sensor Type	Sensor/Devices Operations
pH	Measuring acidity/alkalinity of the soil to determine nutrient availability [51–53].
Motion Detection	Determination of the location of animals and field machinery, detection of motion of unwanted pests on the farm and generating alerts to farmer [54].
Ultraviolet	Monitoring UV for the effective growth of crops [55].

Table 4. *Cont.*

Sensor Type	Sensor/Devices Operations
Passive Infrared (PIR)	PIR sensor traces the range of a person's movement in the field. The sensor also has a light detection property: while tracking an object, rising temperatures are converted into voltage for analysing crop growth [56].
Soil moisture	Measures the quantity of water and level of moisture across the field [57]. Utilised to monitor the greenhouse irrigation system [58].
Temperature	Changes in the soil temperature affect the absorption of soil nutrients and moisture. Utilised to map the exact amount of nutrients in soil and the water surface [59].
Humidity	Measuring the temperature and moisture content of the air to determine humidity in air and its potential impact on the growth of plant leaves, photosynthesis and pollination [60].

5.1. Haystack Monitoring

Currently, the method most commonly recommended to farmers to monitor the temperature of stored hay is to push a crowbar into the stack. The crowbar is then left for approximately two hours and upon removal the length of time the crowbar can be held is an indication of stack temperature (Table 5) [61–63]. An alternative method is to create a temperature probe from a length of metal pipe. One end is flattened with holes then drilled into that end and the pipe pushed into the stack. A thermometer on a length of wire is then inserted into the pipe, left for 15 min and retrieved [61,63]. Both of these methods need to be repeated at a number of locations across the stack. They also have similar limitations: (a) the need to take multiple measurements is time-consuming and (b) they will only reach one to two metres into the stack [61].

Table 5. Temperature interpretation using a crowbar [61].

Crowbar Status	Temperature (°C)	Management
Can handle the bar with no discomfort	<50	Check daily
Can handle for short time only	50–60	Check twice daily, remove machinery from shed (if present)
Can only touch bar briefly	60–70	Check every 2–4 h, move hay to improve airflow
Bar is too hot to hold	>70	Call Fire Brigade, do not walk on stack

Other non-quantitative methods used looking for steam rising from hay, condensation of corrosion under the shed roof, mould or unusual odours and slumping of sections of the stack [63].

More recently, sensors that record, log and transmit temperature data from haystacks or sheds have become commercially available to Australian farmers. These include Quanturi haytech (farmscan.com.au/pages/haytech), Incyt Hay Storage Monitoring (incyt.com.au/collections/microclimate-monitoring) and HayShepherd (shepherdmonitoringsystems.com.au). These either measure the temperature within the bale, stack or under the shed roof and transmit the data using wireless or satellite networks.

5.1.1. Moisture

Moisture is a key determinant for the potential self-combustion of hay bales. Thus, moisture content should be measured as it precedes the combustion itself and if below a certain threshold precludes the event of a haystack fire. The inconsistency due to irregular moisture sources such as dew or steam can be reduced by taking an intrusive sample past the surface layer of the bale [64].

Moisture content of a given material can be measured by four different methods, such as, absolute methods, wet chemical methods, electrical methods and spectrometric methods [65]. Absolute methods directly determine the actual moisture content of a material and therefore can be used as reference methods. Wet chemical methods use various chemical reagents to directly measure the moisture content. Finally, electrical methods use electrical energy and spectrometric methods use light energy to indirectly correlate with actual moisture content of a given material [66].

Oven Drying

Oven drying is the standard method for determining the moisture content of a given material. The formula for the estimation of moisture content of a given material can be expressed as follows, according to [66]:

$$\text{Moisture Content (\%)} = (\text{Total Loss in Mass}/\text{Wet Sample Mass}) \times 100$$

Drying temperature varies with sample types. For example, lucerne contains volatile compounds that can be destroyed when dried at high temperature levels. So, samples containing such volatile compounds are recommended to be dried at 55 °C for 72 h to avoid degradation of additional proteins, which is not considered a part of plant moisture content [67].

Conductivity Sensors

Conductivity is the measure of a material's ability to allow electric current to pass without transferring its energy into heat. This measure varies with moisture because the cellulosic fibre which makes up most of the hay is an insulator. When moisture is added, it increases the conductivity through the transfer of ions into solution and saturation of the fibre matrix [64]. This conductivity is measured in Siemens, which incorporates the surface area of the electrode, distance between the electrodes and the resistance met by current passing from one electrode to the other.

Electric conductivity sensors can be arranged on the same plane or separated entirely, providing diverse potential configurations. The current must overcome the resistance, requiring the electric signal to be developed for the distance between electrodes and the material resistance range [68]. The resistance of the material can vary with density, plant type, ambient temperature and the source of moisture. Various contact types can be used for electrical signal transmission, including pins, probes and electrodes. Previous research has questioned the accuracy of conductance-type sensors tested with a square baler [69].

Capacitance Sensors

A capacitor allows electric potential to be stored between plate electrodes. The material separating the plates, distance between the plates and area of the plates determines the quantity of potential energy storage [70]. The dielectric constant describes the permittivity of the material between the plates. For moisture sensing, the material between the plates is tested for permittivity, which changes with water content because the dielectric constant of water is much larger than hay [68].

The depth of the reading is determined by the field distribution. Though this is not well modelled to define the exact depth, it can be optimized by relating the distance between the plates [70]. The depth of reading can also be increased via the addition of a copper back plate to direct the field away from the sensor [71]. Though these relationships have been noted, there are no final relations for the field distribution and the depth could only be optimized but not directly known from design parameters. This method has been tested to produce accurate results, though the variance of precision is widely based on the implementation environment. There is a high possibility for the recorded signal to be influenced by the incoming current frequency or possible material interference with the field. This requires significant signal filtering to be implemented to produce reliable results [72].

Capacitive sensors are not sensitive to the bale density or volume being tested [73]. The two main configurations for capacitive sensing are parallel and planar based on fringe effect theory [74]. Parallel is widely used in lab applications as the standard capacitive configuration. The planar configuration produces a fringe field that is less restrictive to configuration, though this has not yet been used in any industrial agricultural applications.

Microwave Sensing

A microwave is electromagnetic radiation with an approximate wavelength of 1 mm to 1000 mm and a frequency in the range of 0.3 gigahertz (GHz) to 100 GHz [75]. Moisture measurements in the microwave region of the electromagnetic spectrum can occur in several ways, including transmission/absorption and reflectance [76]. Some microwave sensors can operate at a distance from an object of interest, while other types can be mechanically joined with it [77]. The potential for a material to absorb energy from certain frequencies increases proportionately with the dielectric constant. This allows the determination of water content relative to solids because the dielectric constant of fibrous solids is around 4, while that of water is around 80 [78,79].

Microwave sensing was shown to be very accurate ($R^2 = 0.867$) on a large square baler with maize material with up to 28.9% moisture content when comparing measured vs. actual moisture in the maize bales [80]. The dielectric constant relates field intensity in a space under vacuum to a time when the material is present. It is important to note that this constant varies with temperature, density and moisture content [79]. The antenna can then detect the waves that have reflected from the material or those which passed through to identify a change in frequency. Thus, the microwave system provides a non-intrusive measurement of the cross section of the bale. Though a surrounding metal structure will produce reflective interference, it has been found to be a constant linear relationship, allowing the error to be removed through calibration [81].

Behringer [69] investigated a method utilising microwave reflectance with promising results for lucerne square bales but concluded that there was not enough data to verify the accuracy of this method. Microwave transmission and absorption is another type of microwave moisture measurement where two different types of antennas are engaged. Firstly, a transmitting antenna sends a microwave signal, while on the other hand, the receiver antenna determines the extent of microwave signal energy transmitted through. At the same time, absorption can be calculated and correlated with the moisture content of the given material.

Factors such as the bulk density of the given material and the depth of the material through which the signal is transmitted may affect the sensor's accuracy. Behringer [69] built a microwave transmission system for square bales. While there was limited success, it was discovered that their design was not accurate or precise for lucerne, in one test the sensor showed no sensitivity to moisture when the sample's actual moisture ranged between 11% and 22% moisture.

Near-Infrared Sensors

Finally, near-infrared sensors are a new technology often used in industrial and laboratory settings. The near-infrared spectrum contains strong absorption bands for hydrogen bonds which can be used to elucidate the water content in a solid material. This type of sensor emits near-infrared light at approximately 970 nm, which is absorbed by the tested materials' surface [68].

The light reflected to the sensor is from dry matter, which is proportional to the moisture content in the material. This makes near-infrared a surface level measurement which requires a clear lens to maintain an acceptable state of calibration. The process is non-destructive and non-intrusive, which has enabled its widespread use on food processing lines. The largest influence on the reading is from variations in the sample temperature [82]. This method requires the most significant signal processing because many wavelengths must be monitored and compared. Some of the light is absorbed or transmitted, while the rest is reflected. Higher absorption will occur with a decrease in the amount of reflected light at higher moisture contents in the tested sample. The amount of reflected light at specific wavelengths, ranging from 200 to 2200 nm, can be used to determine the moisture content. The amount of light that is transmitted through a material is minimal.

One limiting factor is that NIR light only penetrates the outer surface of the material tested and does not reflect the physical properties of the material underneath a sample's surface [69]. Behringer [69] conducted tests with two models of sensors, one in both the laboratory and the field, and the second only in the laboratory. The first sensor did not adequately estimate lucerne silage or wet maize silage moisture contents in either the laboratory (static test stand) or the field environments (mounted on a silage chopper). The second sensor was accurate in static laboratory testing, with 94% of the data for wet corn silage within ±2% of the actual moisture content. However, subsequent field testing with a silage chopper showed that the accuracy within ±2% decreased to 81% of all samples collected. No testing was conducted on either sensor with lucerne hay bales [69].

5.1.2. Temperature

Temperature sensors may also be employed to measure heat emitted by the bale. The four main types of contact temperature sensors are thermocouples, resistant temperature detectors (RTD), thermistors and silicon based integrated circuit boards (PCB), all of which have their advantages and disadvantages (Table 6).

Table 6. Advantages and disadvantages of the four main types of temperature sensors, adapted from Reverter [83] and Hayat et al. [49].

	Thermocouple	**Resistance Temperature Detectors (RTD)**	**Thermistor**	**Integrated Circuit Sensor (ICs)**
Temperature range	−100–500 °C	−50–250 °C	−50–130 °C	−40–150 °C
Accuracy	±1–4 °C	±0.2–1 °C	±0.05–0.5 °C	±0.5–1 °C
Sensitivity	Low	Medium	High	Low
Linearity	Medium	High	Low	Medium–High
Response time	5–80 s	1–8 min	0.2–10 s	0.5–100 s
Self-heating	No	Yes	Yes	Yes
Cost	Medium–High	High	Low	Low
Power source	None required	External	External	External
Other	Wired communication only	Larger in size, good immunity to electrical noise	Small size availability	Small size availability, calibrated during production
Main uses	Extreme conditions (e.g., aircraft exhaust gases)	Food and pharmaceutical	Household and automotive	Thermal compensation and management of other components

Thermocouples

One of the most inexpensive and robust temperature sensors are thermocouples. Thermocouples can operate over a relatively wide temperature range. Thermocouples are made by joining two dissimilar metals such as iron and copper/nickel (constantan) at one end, thus producing a small open circuit at the other end, which measures voltage which is a function of temperature [83]. The joined end merging two dissimilar metals that directly probes a given material is called the hot end/junction. The other end is referred to as the cold end/junction. A small voltage, generally referred to as EMF (electro-motive force) is created when there is a difference in between the two hot and cold junctions. Generally, the voltage is nonlinear with respect to temperature. However, for small changes in temperature, voltage is approximately linear; therefore, EMF can be measured and used to indicate temperature [84].

Resistance Temperature Detectors (RTDs)

Resistance temperature detectors (RTDs) are temperature-sensing devices for which variations in temperature result in measurable changes in resistance. RTDs are usually made from platinum; however, nickel or copper-based devices are not rare with different shapes such as wire wound and thin film [83]. Typically, RTDs are connected to a constant current source. The resistance of an RTD can be measured by estimating the resulting voltage followed by applying a constant current [85]. RTDs exhibit consistency towards a linear resistance to temperature curves; therefore, any nonlinearity to temperature change is highly predictable and repeatable.

Thermistors

Thermistors are similar temperature-sensing devices to RTDs, whose resistance varies with temperature change. Thermistors are made from semiconductor materials. Resistance of thermistors is determined in a similar way to RTDs, but thermistors exhibit large resistance change for a minimum temperature change. Thus, thermistors maintain a highly nonlinear resistance to a temperature curve (Table 6). Due to high sensitivity, thermistors are generally ideal for set-point applications [86].

Silicon Based Integrated Printed Circuit Board (PCB, ICs)

Integrated circuit sensors are available with a variety of interfaces, such as analogue or digital. In the case of digital, a serial peripheral interface, SMBus/I2C or 1-Wire, is very common. However, these are further classified into various types such as, voltage output, current output, digital output, resistance output silicon or diode temperature sensors [83]. The latest semiconductor temperature sensors are highly accurate, offering high linearity from a −55 °C to +150 °C operating range. The output can be measured by internal amplifiers to convenient values, such as 10 mV/°C. Their application is limited to cold-junction compensation circuits in wide range temperature thermocouples [87].

Silicon temperature sensors simplify the challenges related to broader temperature monitoring. These sensors differ from others in various ways. First of all, silicon temperature sensors offer broader temperature monitoring and can operate over a −55 °C to +150 °C temperature range [83]. Secondly, these sensors differ in functionality as they have either analogue circuits or analogue-sensing circuits with digital input/output and control registers to provide alert functions compared to traditional compensation circuits. Temperature is continuously measured and monitored at any time as the digital output sensor usually contains a temperature sensor called an analogue-to-digital converter (ADC). These sensors are usually microprocessor-based systems that offer reliable temperature monitoring over time [88]. Moreover, the high and low temperature threshold can be programmed so that the host can receive a notification when temperature hits the threshold limit. These sensors are highly compatible with digital temperature readings in °C and therefore are designed to measure temperatures from 0 to 70 °C with ±0.5 °C accuracy.

Digital temperature sensors are simple and advanced equipment as no calibration is required at specific temperatures. The sensor output supports balanced digital reading thus providing a precise reading in °C. These sensors provide some advanced features such as not needing excess components like an ADC converter and being easier to use compared to a thermistor that provides non-linear resistance with temperature variation [49].

5.1.3. Fire Sensors and Fire Detection Systems

Sensors that are normally used to detect one or more of the fire products (namely, smoke, heat, infrared and/or ultraviolet light radiation, or gases) resulting from a fire event are known as fire sensors [89]. These sensors may be further categorized into the three main fire development stages (Table 7).

Table 7. Sensors based on the development stages of fire.

Fire Stage	Combustion Product/s	Types of Sensors
Development, ignition, pyrolysis phase	Invisible smoke aerosols and fire gases	Gas sensors and aspirating systems
Smouldering fire	Visible smoke and aerosols	Gas sensors, optical smoke detectors and heat detectors
Open fire	Heavy smoke and heat development	Optical smoke detectors and heat detectors

Fire detection systems are basically developed as a complete package that involves both detection and action [89]. Therefore, several other devices are joined together to work as a whole. The overall system is more than just a sensor; typically, the sensor is connected to an alarm system which makes a loud sound when the sensor activates. Now, the working principle of the sensor is based on the simultaneous measurements of temperature, smoke and combustion products including oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), water vapor (H_2O), hydrogen cyanide (HCN), acetylene (C_2H_2) and nitric oxide (NO). Fire detection algorithms utilise data from sensors to provide a potential fire alarm based on the increase in smoke and other fire products [90].

6. Introduction of 'Smart Agriculture' for Haystack Management

6.1. Definition

Smart agriculture incorporates recent technologies such as a Global Positioning System (GPS), the Internet of Things (IoT), Big Data, Cloud Computing, and Artificial Intelligence (AI) along with sensors and actuators into agricultural systems (Figure 5).

Smart agriculture utilises sensing nodes placed in target areas, such as broadacre crops, pastures, greenhouses and irrigation channels, which can collect data of interest in real-time. Common data types collected include temperature, humidity, light, pressure, gas concentration, moisture content, electrical conductivity and imagery. Generally, collected data is aggregated into a cloud-based system for processing and delivered to the end user in the appropriate format. These data may also be used in a feedback loop to provide automation of actuators based on algorithms and AI (Figure 6).

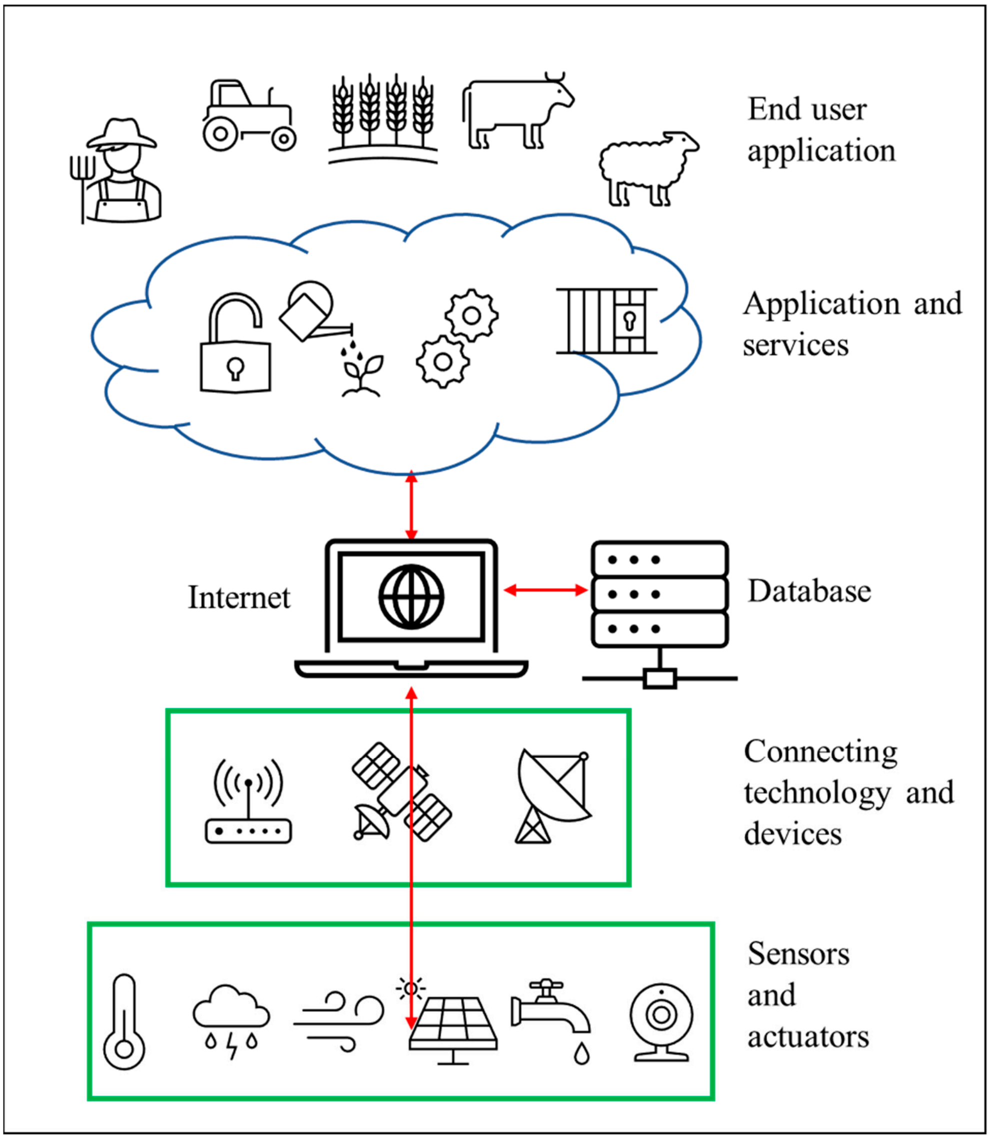

Figure 6. Components of the structure of smart agriculture. Adapted from de Araujo Zanella et al. [91] and Gsangaya et al. [86].

6.2. Internet of Things (IoT)

The term IoT was first coined in 1999 with reference to supply chain management [92]. The concept of IoT revolves around the word "smartness"—"an ability to independently obtain and apply knowledge". Therefore, IoT refers to the "things or devices and sensors" that are smart, uniquely addressable based on their communication protocols, and are adaptable and autonomous with inherent security (Table 8) [93].

At present, IoT serves both individual and professional domains. For individuals, IoT significantly enhances living standards by enabling e-health services, smart home solutions and innovative educational experiences. In the professional arena, IoT finds application in automating tasks, optimizing supply chains and transportation, enabling remote monitoring and streamlining logistics operations [94].

With the advancement of current technology, environmental monitoring solutions offer additional facilities in terms of management and decision making.

Security and privacy are key requirements for IoT applications. Security and privacy are one of the major open issues in IoT's architecture as end-user data should be protected from eavesdropping and interference. Data should be authenticated, and its integrity must be maintained at the user end (Table 8). Various cryptographic algorithms are proposed for data authentication, but it possesses serious energy and bandwidth consumption issues [94].

Table 8. The requirement for IoT-based agriculture and farming activities.

Requirement	Reasoning
Connectivity	Stable internet connectivity is the most important and basic requirement. The connection needs to be reliable, withstand various climatic conditions and be available throughout the area of interest.
Sensors and hardware	Appropriate sensors are required. Quality, security and privacy of sensors need to be considered before implementation ensuring long and sustainable use.
Data analysis tools	Tools or software to analyse the data using various algorithms and machine learning to gain predictive insights are required.
Secure internal systems	The software should have proper security which prevents the stealing of data. The software should also be easy to use for the farmers and accessible.
Management system	Sensors require maintenance at regular intervals of time. They are sensitive devices that require cleaning and the replacement of batteries and degraded components.

6.3. Communication Technologies and Protocols

Communication with the device may be achieved through multiple protocols: a text message sent directly from the device, the design of an antenna to send out a signal, and other means of communication. A key factor in IoT technology is the need for M2M (machine to machine) communication which traditionally has utilised a mobile data service using cellular networks. However, many mobile operators are switching off their GPRS and 3G networks, meaning alternatives are required for M2M communication [95]. There is a wide range of advanced wired and wireless communication technologies available. Protocols are being developed for the interconnection of M2M (machine to machine) communication for the precise and efficient monitoring, storage of sensor information and data communication.

Both wired and wireless technologies have their own privileges considering the purpose and area under coverage. Wired technologies (Ethernet, serial communication (RS232/RS422/RS485), etc.) tend to be more secure as they are typically installed behind a Local Area Network (LAN) firewall that prevents interference of transmitting data. They have fast data transfer speeds due to a minimum of signal interference/distortion by physical hindrances (walls, ceilings, etc.) or from any other electronic devices. Wired communication devices tend to be more reliable as these are less prone to disconnections, and therefore, do not need constant debugging and troubleshooting. Despite the widespread use of wired technologies over the years, the literature suggests that wireless technologies are now becoming increasingly popular over wired technologies due to vast advancements in speed, security, reliability and the variety of options available [49,96–99]. Wireless technologies (Zigbee, WiFi, Bluetooth, EnOcean, etc.) are more scalable, mobile and free from extensive hardware installations. Therefore, no additional cable installation/repair and labour costs are required, which is generally economical to the end user.

In remote areas of Australia where connectivity via cellular (2G/3G/LTE) networks is not available, low earth orbit (LEO) satellites may be used to overcome communication limitations [100]. During communication, the distance between a satellite transmitter and a LEO satellite varies between 500 and 2500 km, depending on the altitude and elevation of the satellite. In comparison, terrestrial IoT solutions might work within a few tens of kilometres range. Considering all the advantages and limitations, both sets of technologies have a place in the market; therefore, it is vital to assess the viability and suitability of each technology prior to selection to ensure maximum performance to meet their respective requirements. Table 9 presents an overview of the most prominent and commercially available wired and wireless communication technologies and protocols with their key characteristics compared.

Table 9. Key characteristics of prominent wired and wireless communication technologies (updated from [49]).

Technology (Standard)	Coverage Range (m)	Theoretical Data Rate	Maximum Number of Nodes	Power Consumption	Market Adoption
Ethernet (IEEE 802.3)	100	10 Mbps–100 Gbps	1 per wire (254 on a subnet)	Low	High
PLCC (Insteon, IEEE 1901, CE bus, LonWorks)	300–3000	13 kbps–200 Mbps	500–1000	Low–High	Low
Serial Comm. and Modbus (RS232, RS422, RS485)	15–1200	1–10 Mbps	32 typical. Up to 256 with some ICs	Low	High
Zigbee (IEEE 802.15.4)	10–100	250 kbps	255	Low	High
Bluetooth (IEEE 802.15.1)	10–50	2–24 Mbps	8	High	High
WiFi (IEEE 802.11 a,b,g,n,ac)	50–70	11–1300 Mbps	255	High	High
EnOcean (EnOcean standard)	20–200	125 kbps	232	Low	Low
BACnet (ANSI/ASHRAE 135)	1200	9.6–115.2 kbps	32 typical, up to 128	Low	Low
6LoWPAN (IEEE802.15.4)	10–100	250 kbps	100	Low	Low
Z-Wave (Z-Wave Alliance)	30–300	100 kbps	232	Low	Low
LoRaWAN (LoRa Alliance)	10,000	0.3–50 kbps	2000–3000	Low	Low
LEO (Low Earth Orbit Satellite)	500–2500 km	1–40 Mbps	>1 million	Low	Low
NB-IoT (Narrowband IoT)	~1000 (urban) ~10,000 (rural)	200 kbps	Up to 50,000	Low	High

The advantages of IoT for monitoring haystacks over current methods are threefold. Firstly, compared to many of the current methods the data obtained are quantitative not qualitative, meaning greater accuracy (Tables 5 and 6). Secondly, it has the ability to obtain multiple measurements at different locations in a short period of time (Table 9). Finally, this data can be obtained remotely and transmitted to a central location with auto-generated alerts when pre-determined thresholds are exceeded.

Limitations do exist for the use of IoT in haystack monitoring. In Australia, many haystacks or sheds are located away from other buildings and/or an electricity supply. The coverage range and power consumption may impact the suitability of some communication technologies to transmit the data obtained to the farmer or office (Table 9). While the vast majority of the Australian population (up to 99.5% depending upon carrier) have mobile phone coverage, in rural Australia there are still areas where the coverage is unreliable [101]. This limits the suitability of some communication technologies. Likewise, as the temperature of hay bales can increase rapidly (up to 5 °C in one hour (unreported data), the need for frequent monitoring may currently preclude the use of other technologies such as LEO satellites, which do not provide coverage 100% of the time.

Finally, the large variability between individual bales in the parameters which may induce spontaneous combustion will require a large number of sensors to significantly reduce fire risk in a large stack. With a large number of sensors required, the ability to communicate the data obtained (Table 9) and the cost of the monitoring system may limit the rate of uptake by hay producers.

7. Conclusions

In conclusion, hay fires pose a significant threat, with spontaneous combustion being a leading cause. Due to the lack of understanding about spontaneous combustion as a major cause of fires, this phenomenon is often misinterpreted and underestimated. Additionally, in reality this process of combustion is not as spontaneous as the name suggests. Therefore, the accurate monitoring of specific parameters may be a useful preventative tool.

Moisture content during baling and storage plays a crucial role in determining the magnitude and duration of the heating process leading to such fires. However, with proper curing of hay to below 20% moisture concentration before baling and regular monitoring, the risk of hay fires may be reduced. Advances in agriculture technology offer devices and sensors to accurately monitor critical parameters providing quantitative data over time to assist in accurate decision making, but to truly mitigate the risk, a cost-effective, low-power and robust device with remote communication capabilities is needed. Such a device could greatly reduce the risk of hay fires, minimising farm income loss and stress as a result and support smart agriculture techniques.

This review emphasises the need for integrated, multi-faceted approaches combining technological advancements with traditional agricultural practices to effectively mitigate the risks associated with haystack fires. It is time for the industry to invest in such solutions and tackle this persistent problem.

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