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Biodegradable Plastic - An Opportunity towards Sustainability

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ABSTRACT: Plastic usage is increasing the number of pollutants in the environment. Plastic particles and other plastic-based pollutants are found in our environment and food chain, posing a threat to human health. From this perspective, the biodegradable plastics material focuses on creating a more sustainable and greener world with a smaller environmental imprint. This assessment should consider the entire life cycle assessment of the objectives and priorities for producing a wide range of biodegradable plastics. Biodegradable plastics can also have properties similar to traditional plastics while also delivering additional benefits due to their minimised impact on the environment in terms of carbon dioxide, as long as appropriate waste management includes such as composting, are contained. The demand for cost-effective, eco-friendly materials increases to reduce waste management and pollution issues. This study seeks to comprehensively understand biodegradable plastics production and applications research, product prospects, sustainability, sourcing and ecological imprint. Academic and industry interest in biodegradable plastics for sustainability has exploded in recent years.

KEYWORDS: plastic, biodegradable, sustainability, environment, management, pollution, ecological

I. INTRODUCTION

In line with the recent economic growth, especially in developing countries, human concern for the environment has increased over time.[1-3] This paradigm shift has influenced many developing countries to pay more attention to the issues related to the use of synthetic plastics. Both industry and consumers are intrigued to discover the: economic characteristics, environmental consequences, and social attitudes to the benefits of biodegradable plastics. Biodegradable plastics are useful in packaging, agriculture, gastronomy, consumer electronics, and the automotive industry. This paper seeks to explain the prospects of biodegradable plastics regarding social, economic, and environmental sustainability and recognizes the latest advances in enzyme-based biodegradation of plastics in order to reduce plastics' negative effects and to make the environment safe. A multi-disciplinary strategy is a unique approach, with studies carried out across the triple bottom line (TBL) approach on three distinct sustainability concepts (economic characteristics, environmental consequences, and social attitudes). These three subjects were carefully chosen for their respective targets.[4-8]

Since the origin of synthetic polymers, they have become the indispensable part of the human world because of their wonderful properties and characteristics such as ductility, malleability plasticity, lightweight, high durability, good flexibility, cost effectiveness, easy availability and mass production [1-10]. Plastics can be easily moulded into different shapes (boxes, tubes, films, fibres, bottles, plates, etc). Nowadays, these polymers are fulfilling our everyday needs like clothing, cosmetic items, toys, household utilities, TV screens, automotive parts, electronic items, IT tools, food packaging medical equipments, etc [11-19]. They play a vital and ubiquitous role in human lives. Initially innovation of plastics was thought to be very beneficial but as the time passed, it has proved to be more hazardous to the environment [20-23]. Plastics are derived from non-renewable petroleum resources, the overuse of which led to depletion of these natural resources. These contain organic substances and improper disposal of them causes death of millions of animals because of choking. These have harmful effect not only on aquatic organisms but also on terrestrial animals, as they reduce the soil fertility and increases the chances of eutrophication [24-25]. The biggest problem associated with plastics is that they are nonbiodegradable and persist in the environment for hundreds and even thousands of years [26-36]. Plastic waste disposal has become a serious environmental menace worldwide [37-38]. This problem will get worsen and continue to increase exponentially if

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the worldwide production and use of plastic and its products will continue to rise at their current rates. Burning of these polymers is also destructive for the environment as it releases hazardous gases and chemicals which can lead to the risk of serious respiratory illness, nausea, pulmonary and cardiac diseases, skin rashes, headaches, cancer, compromised immunity, endocrine disruption, birth defects and severe damage to the reproductive and nervous system in humans [39-40]. The emitted greenhouse gases such as methane, nitric oxide, carbon dioxide increase global warming effect [41-42]. Moreover, plastics disintegrate into smaller fragments called microplastics. These prove to be dangerous for marine animals when get mixed into oceans, seas and other water bodies and reports of microplastics found in human bodies are also there [43-45]. Therefore, it is necessary to develop eco-friendly and biodegradable substitute of the petroleum based conventional plastics [46]. The environmental consequences resulted from the use of plastics and their products has led the emanation of biodegradable plastics in the arena of research [47-56]. These are considered to be economically and environmentally feasible to replace the traditional petrochemical plastics [57-64].

Biodegradable plastics are a kind of environmentally friendly plastic which can be deduced from renewable resources such as biomass, starch, fats and oils [65-69]. Some waste materials for examples, food, agricultural and vegetable wastes, renewable feedstocks for example, biomass serve as the key sources of bioplastics which results in not any environmental pollution, no loss of fossil fuel, and ultimately no harm to mankind [70]. A population of microbes can also be helpful to obtain biodegradable plastics from bio-wastes [71]. Biodegradable plastics degrade inherently in the environment. This process is accomplished when microorganisms, exist in environment, metabolize and breakdown the structure of biodegradable plastics into simple compounds that are not harmful for the environment. [72]. There are two kinds of biodegradable plastics: one can decompose in aerobic process (composting) and the another can decompose in anaerobic environment (landfill) [73]. It degrades into methane (CH4), carbon dioxide (CO2), water (H2O) and biomass through microorganisms in a definite timescale and in definite environments [74]. For example, Polylactic acid (PLA), thermoplastic starch and Poly-3-hydroxybutyrate (PHB) based biodegradable plastic etc. Biodegradable plastics can be an ideal substitution for conventional / traditional plastics due to their similar applications [75-77]. These are a feasible alternative to achieve environmental sustainability due to their biodegradability and biocompatibility and the matter of fact that they are made of renewable and biogenic raw materials such as starch, wood pulp and vegetable oils which make them efficient for applications in biomedical, medical implants, piping, agricultural sector, packaging, textile industries, phone cases, bag industry, containers, carpets, etc and other valuable industrial applications [78-79]. The utilization of renewable feedstock and biodegradability are foremost advantages for the use of biodegradable plastics[80].

Most of the environmental problems caused by plastics can be abolished by utilizing bio-based fibres and biopolymers produced from natural and renewable bioresources. Biodegradable plastics prove to be a momentous invention that can pay significant contribution for building the bioeconomy and switch the reliance from conventional fossil fuel-based resources to bio-based products [10]. Biodegradable plastics are eco-friendly because their manufacture results the discharge of less CO2, which causes global warming. Utilization of renewable feedstock for the production of plastics can lower the amount of greenhouse gases (such as CO2 and CH4) emitted into the atmosphere in comparison of conventional plastic synthesis from fossil fuels[81]. Biodegradable plastics possess a number of wonderful characteristics that make them reliable and worthy alternative of fossil fuel based conventional plastics. Varied properties of biodegradable plastics are: [82-88]. a) Based on renewable resources and biomass b) Biodegradable i.e., degrade in the environment c) Less energy is utilized during their production process d) Carbon neutral i.e., quantity of carbon dioxide released during their degradation is approximately equal to CO2 absorbed by plant during the process of photosynthesis e) Environment-friendly as these do not cause any pollution

Biodegradable plastics are used for a large variety of applications. They have a largest market segment in packaging industry. The sustainable nature and biodegradability of PLA, PHA, PBS, starch and cellulose polymers have made them the ideal tools in various applications to substitute many synthetic plastics [89-90]. These have an extensive range of utility in every field such as packaging, textiles, consumer goods, horticulture and agriculture, transport and automotive, adhesives and coatings, construction, electrical and electronics, etc. Packaging sector shares more than half of the total usages of bio-based and biodegradable plastics. Textile industries find approximately 11% share in the total utility. Agriculture sector finds 8% contribution. Rest all sectors comprise the remaining portion of

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applications [91]. The common type of biodegradable plastics that find applications in varied fields are made up of PLA, PHA, Bio-PBS, Starch and Cellulose and their blends with other polymers.

II. DISCUSSION

Polylactic acid is a part of the family of aliphatic polyesters composed of monomeric units of lactic acid. Lactic acid is the -OH group containing carboxylic acid that can be produced by bacterial fermentation from sugars and starch attained from renewable and natural resources [92-93]. PLA has very distinctive features such as shining appearance, good rigidity and transparency and ability to withstand different processing conditions. It has effective heat resistance and mechanical properties [94]. Due to these features, it has a vast area of applicability in different fields [95]. It is mostly utilized in packaging of food items which includes water bottles, cups, plates, cutlery, food trays, films, containers, wrapping papers, etc. Nowadays, PLA fibres are efficiently replacing synthetic plastics from textile industries. These are used in textile industries for making soft baby wipes, sportswear, dresses, drapes, shirts, diapers, hard landscape materials, etc. [93,96]. PLA is blended with other materials to boost its mechanical strength and heat resistance. NEC Corporation in Japan synthesized PLA blended with carbon and kenaf fibres to enhance its thermal stability and flame retardancy. Computer housings have been prepared by using employed blends of PLA with polycarbonate. It also finds utility in chemical and automotive industries for making membrane materials. PLA and its blends have also been employed in human clinical applications. These are used for producing bioresorbable scaffolds that are used to grow living cells in implants, bone support splints, etc. [97-102]. PHAs represent a group of polyesters that are obtained from fermentation by bacteria. These have the potential to substitute traditional petroleum based non-renewable resources. Although PHA are found in different naturally occurring organisms but their production has been mainly employed from microorganisms. These are obtained from various kinds of bacteria which utilize different types of renewable and waste feedstock [103-106]. The process of production of PHA through bacterial fermentation comprises of three steps. The first step involves fermentation by bacteria. The second step comprises of isolation of the products from bacterial cells and the third step involves purification of the products from the fermentation broth [65]. These are thermoplastic biopolymers having varied properties that depend upon their chemical composition and the types of bacteria from which these are obtained. PHAs are biodegradable and biocompatible polymers [107]. PHAs have very well mechanical and thermal properties. These have prominent resistance to moisture content and have smell barrier features [108]. Having unique and varying properties, PHA has been tailored in many packings, industrial, as well as healthcare applications [109]. Materials composed of PHA polymers have been used in food packaging applications such as disposable spoons, forks, food trays, container lids, closures, caps, tubs, knives, plates, etc. PHAs also find utility in injection-molded such as fibres, films, laminates, sheets and coated items. Products such as disposable items, nonwoven fabrics, feminine hygiene products, synthetic paper items, paints, adhesives, foams, waxes, binders, cosmetic items, medical packaging materials, housewares, etc. have also been prepared by using PHAs [96,110]. PHAs and its copolymers are also utilized in biomedical applications. These encompass meniscus repair devices, surgical mesh, sutures, suture fasteners, tissue repair patches, cardiovascular patches, bone plates, stem cell growth, biocontrol agents, antibacterial agents, anticancer agents and memory enhancers and rivets. Use of PHAs in drug delivery has also become an area of its applicability [111- 115].

Polybutylene succinate is an aliphatic and biodegradable polyester that is obtained from condensation of two monomers: succinic acid and 1,4-butanediol. These monomers can be achieved from petroleumbased resources or from bacterial fermentation. Raw materials for Bio-PBS are mainly obtained from monomers of cassava and sugarcane plants. Succinic acid is obtained by glucose produced from renewable resources and 1,4-butanediol is obtained from bio-ethanol. The process of production of bioethanol from sugarcane involves three stages; first is the plantation of sugarcane, second is the transformation of sugarcane into molasses by the use of sugar milling and refining and the third is processing of the molasses into bio-ethanol through fermentation [116-117]. Bio-PBS is semicrystalline in nature with high melting point. Its crystal structure affects its thermal and mechanical features [118]. It has good flexibility, tensile strength, biocompatibility and heat resistance. Copolymers of PBS can be obtained by adding monomers of adipic acid or sebacic acid to improve its mechanical strength and rigidity [119]. Bio-PBS and its blends with other polymers have been employed in a vast area of sectors such as agriculture, packaging, textiles, construction, forestry, healthcare, consumer goods, fishery, automobile industry, electronics,

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interiors etc. [120]. It also finds application in developing bottles, filaments, pots for plants, mulch films, trays, containers, trash bags, hygiene products, laminated paper, gloves, etc. [121]. Plastic utensils, plates, bowls, diapers, etc. are also being prepared by using Bio-PBS. Blends of PBS and PLA are extensively utilized to develop different kinds of fibres, sheets, flat and blown films, etc. Being biocompatible, these are also used in producing packing materials for food items [122].

Starch is the most bounteous polysaccharide that occurs naturally on our planet earth. It is biodegradable, sustainable and renewable resource that is prepared by plants during the process of photosynthesis and stored in the form of their food. Starch can be derived from different sources for example, from tubers like tapioca, potato, etc. from cereals such as rice, wheat, corn, etc. and from cashew nuts [123]. Potato, corn, wheat and cassava are the principal plant sources of starch [124-125]. Starch is comprised of two types of glucose units linked by 1,4- α linkages, one is amylose that is linear component and the another one is amylopectin that is branched component [126-128]. These polymers constitute 98 to 99% of the total weight of starch. The rest 0.5 to 2 % of starch is composed of proteins, non-starch polysaccharides, lipids, ash, etc. The ratio of amylose and amylopectin significantly affects the characteristic properties of starch [129-130]. Starch is abundantly used as biopolymer because of its renewability, biodegradability and costeffectiveness [130-138]. Starch is blended with other polymers and plasticizers to form thermoplastic starch. It has good mechanical strength, thermal stability and less brittleness. The properties of starch depend upon its chemical composition [139-140]. Presently, starch and thermoplastic starch find applications in varied sectors such as pharmaceuticals, food packaging, agriculture and horticulture, engineering, textiles, paints, construction, paper and cardboard industries, automotive industries, etc. [141-143]. Biodegradable materials prepared from starch have extensively been used in production of films, shopping bags, disposable food containers such as cups, plates, trays, etc. overwraps and sanitary products [144]. Packing material for food items have also been obtained from starch-based biopolymers [145-147]. Starch is also used in preparation of mulch films and products needed for controlled release of fertilizers that are effectively used in agriculture Starch and blends with other polymers have also been efficiently utilized in medical sector for producing films for releasing the drug, bone efficient cement, etc. [148- 149].

Cellulose is the primary component present in the cell wall of plants. It is also found in the cell wall of algae and some bacteria. Cellulose has crystalline structure and it comprises of glucose units that are connected by β-1,4-glycosidic linkages. Wood and fibres of cotton are the main sources that serve as raw materials for production of cellulose [150-151]. Cellulose is rigid and hard polymer and has a very high tensile strength that makes it suitable and feasible to be used in formation of biodegradable plastics. It has good thermal stability. Cellulose is modified in the form of cellulose ethers, cellulose esters and regenerated cellulose so that it can be utilized in the production of biodegradable plastics [152-154]. Cellulose has a widespread variety of applications in different areas. Cellulose ethers namely hydroxyethyl cellulose and carboxymethyl cellulose are extensively utilized in production of packaging materials for food, in personal care articles, construction works, paint, adhesives, medical equipments and tools [155]. Fibres and films for packaging have been developed by using cellulose esters like cellulose acetate and cellulose nitrate. Fibres and films made up of regenerated cellulose are efficiently utilized in home furnishing fabrics, clothing and textiles and hygienic disposables [156]. Cellulose is fibrillar in structure and it can be used to develop hydrogels which are utilized in implantation of bones, tissue engineering, effective drug delivery, modelling of cartilage, cell culture scaffolds, absorbance of heavy metal ions, etc. [157-159]. Nanocomposites of cellulose find astonishing applications in the arena of medical and healthcare. These are used for medical implants in both orthopaedic and dental fields. Nanocelluloses and their composites are also efficiently used in production of wound dressing materials which are designed to reduce pain and infection and accelerate reepithelialisation. Magnetically active and 3D printing materials are also being designed by using nano cellulosic materials [160-162].

III. RESULTS

According to European Bioplastics, of the 368 million tons bioplastics produced globally, only one percent is biodegradable and/ or bio-based. Though the bioplastic production is expected to rise more than 300% by the end of year 2026 from its 2021 statistics of 2.42 million tons worldwide but still bioplastic is far away from anchoring the market mainly because of the economics involved in the production of the same. In spite of plastic products being

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widely synthesized and standardized in almost every industry from packaging to pharmaceuticals and their reasonable prices also hinders the acceptance of biodegradable plastics at a large scale [91,167]. Cost of production of biodegradable plastics is aloft than their fossil-based analogues and it cannot be ascribed to a specific input or technology, because the production process involves diverse complex feedstocks, technologies and methods. The methods of synthesizing biodegradable plastics, their technological setup and production conditions vary largely when considered worldwide. The prices of feedstock also become a controlling factor for the cost of biodegradable plastics. However, currently prices of some biodegradable plastics such as PLA is very competitive to the commercially available plastics. It is currently leading the market of bio-based and biodegradable plastics in terms of prices [167,168].

With the increased global focus on sustainable development, people are more concerned about environmental pollution and there is a paradigm shift towards use of biodegradable products like bamboo brush is gradually replacing conventional plastic brushes. Similarly, with the increased R&D in this particular domain, cost of biodegradable plastics is expected to further sink. Additionally, scale of production will also play a crucial role in deciding the economics of biodegradable plastics production. With increased demand large-scale production will impact the price modalities and will drastically reduce the prices of production, conversion into products, management and rest other factors [168,175]. Biodegradable plastics have come to the light after the adverse and destructive effects of plastic pollution on environment have become unavoidable. The emergence of biodegradable plastics is a prerequisite for the sustainable and safe environment. Globally, their contribution in conserving and protecting the environment is significant. The capability of biodegradable plastics as a green alternative to conventional petroleum-based plastics is efficiently utilized in almost every field of life such as packaging of food products and other stuff, electronics, agriculture, paints, adhesives, construction works, pharmaceuticals, textiles, automobiles, etc. Their applicability and utility are expanding day-byday. Overall, investigation is needed to fully explore, establish and enhance the potential of biodegradable plastics, their raw materials with desired properties and applications in various spheres of life so that they can significantly accelerate the protection and sustainability of environment.

IV. CONCLUSIONS

Various researchers have undertaken extensive life cycle assessments of biodegradable polymers to determine whether these materials are more energy efficient than polymers made by conventional fossil fuel-based means. Research done by Gerngross, et al. estimates that the fossil fuel energy required to produce a kilogram of polyhydroxyalkanoate (PHA) is 50.4 MJ/kg,[62][63] which coincides with another estimate by Akiyama, et al.,[64] who estimate a value between 50-59 MJ/kg. This information does not take into account the feedstock energy, which can be obtained from non-fossil fuel based methods. Polylactide (PLA) was estimated to have a fossil fuel energy cost of 54-56.7 from two sources,[65] but recent developments in the commercial production of PLA by NatureWorks has eliminated some dependence of fossil fuel-based energy by supplanting it with wind power and biomass-driven strategies. They report making a kilogram of PLA with only 27.2 MJ of fossil fuel-based energy and anticipate that this number will drop to 16.6 MJ/kg in their next generation plants. In contrast, polypropylene and high-density polyethylene require 85.9 and 73.7 MJ/kg, respectively,[66] but these values include the embedded energy of the feedstock because it is based on fossil fuel.Gerngross reports a 2.65 kg total fossil fuel energy equivalent (FFE) required to produce a single kilogram of PHA, while polyethylene only requires 2.2 kg FFE.[63] Gerngross assesses that the decision to proceed forward with any biodegradable polymer alternative will need to take into account the priorities of society with regard to energy, environment, and economic cost.Furthermore, it is important to realize the youth of alternative technologies. Technology to produce PHA, for instance, is still in development today, and energy consumption can be further reduced by eliminating the fermentation step, or by utilizing food waste as feedstock.[67] The use of alternative crops other than corn, such as sugar cane from Brazil, are expected to lower energy requirements. For instance, "manufacturing of PHAs by fermentation in Brazil enjoys a favorable energy consumption scheme where bagasse is used as source of renewable energy."[68]Many biodegradable polymers that come from renewable resources (i.e. starch-based, PHA, PLA) also compete with food production, as the primary feedstock is currently corn. For the US to meet its current output of plastics production with BPs, it would require 1.62 square meters per kilogram produced.[69]

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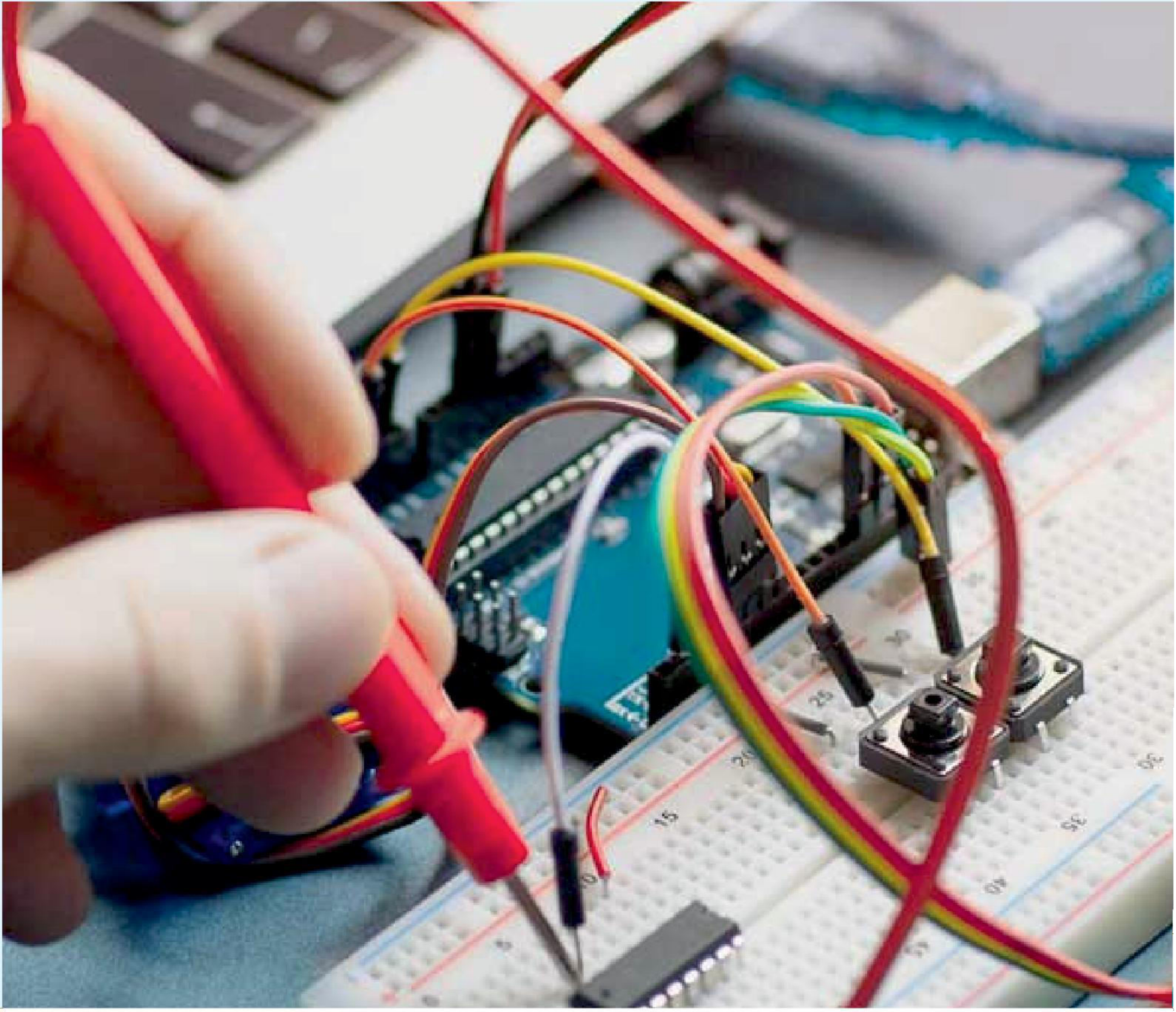

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