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Review Article

Human Hair "Waste" and Its Utilization: Gaps and Possibilities

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Human hair is considered a waste material in most parts of the world and its accumulation in waste streams causes many environmental problems; however, it has many known uses. Preventing waste of such a material requires both addressing the problems in the current usage and developing its utilization systems at locations where they are missing. With focus on developing systematic utilization of human hair waste, this paper first reviews the possible uses of human hair gathered from large scale trades, local/traditional knowledge, upcoming innovations, and scientific research; along with the socioeconomic systems that have evolved around the known uses. Concerns and gaps in these systems are identified and possible directions to address these gaps are discussed. For expanding hair utilization to new contexts, important considerations such as knowledge, skill, and technology requirements and potential markets are discussed. Finally, a policy framework for socially and environmentally healthy utilization of human hair is outlined. This study shows that human hair is a highly versatile material with significant potential in several critical areas such as agriculture, medical applications, construction materials, and pollution control. Moreover, these uses are diverse enough for entrepreneurs ranging from unskilled to highly technical individuals and for the wide variety of human hair waste available in different locations.

1. Introduction

Human hair is a material considered useless in most societies and therefore is found in the municipal waste streams in almost all cities and towns of the world [1]. In rural areas or areas with low population density, the hair is thrown away in nature where it slowly decomposes over several years, eventually returning the constituent elements, namely, carbon, nitrogen, sulfur, and so forth, to their respective natural cycles. In urban areas or areas with high population density, it often accumulates in large amounts in the solid waste streams and chokes the drainage systems, posing a multifaceted problem. Due to slow degradation, it stays in the dumps/waste streams for long occupying large volumes of space. Over time, leachate from these dumps increases the nitrogen concentration in the water bodies, causing problems of eutrophication. Burning of human hair or the waste piles containing them—a practice observed in many parts of the world—produces foul odor and toxic gases such as ammonia, carbonyl sulphides, hydrogen sulphides, sulphur dioxide, phenols, nitriles, pyrroles, and pyridines [2]. Open dumps of hair generate hair dust which causes discomfort to people near them and, if inhaled in large amounts, can result in several respiratory problems. Oils, sweat, and other organic matter sticking to the hair rot over time and become a source of foul odor and breeding ground for pathogens.

The best way to address such problems is to develop systems which utilize the waste material as a resource. In addition to reducing waste, it contributes to the economy. As a potential material resource, human hair has the advantage that it is completely biodegradable, renewable, and available in every locality.

Interestingly, while the hair is dumped as waste in most places, certain kinds of high quality human hair and its products are also traded internationally at large scales. In 2010, India alone exported ~1 million kg of human hair and its products worth US $238 million, and total global imports were valued at US $1.24 billion [3]. Largely centered on wigs, hair extensions, and so forth, this trade also has been a source of many of the above mentioned environmental and health problems. Due to hair dust and decaying hair, workers of many hair-processing units in India have increased cases of

tuberculosis and respiratory tract infections [4, 5]. Improper disposal of hair and other processing waste in many of these units has been a source of pollution and legal conflicts [4, 6]. In one such case of Jwalapuri market in New Delhi, India [6], the traders used to put the waste hair to fire. Protests and legal efforts by neighbors in 1998 led to relocation of the processing units to villages in outskirts of New Delhi (personal discussions with Malik, I., 2012), but no systemic improvement was attempted in the processing practices. In Eluru district in Andhra Pradesh (India), dumping of large amount of hair waste from the processing units at the banks of a local river led to pollution, health problems, and conflicts, but the authorities could not resolve the issue because they found no way to deal with the hair waste other than to burn or dump it [4]. These examples show that in spite of a large scale economy running around human hair, there had been no systemic thinking about environmentally safe management of the human hair waste.

There is a great need therefore to develop utilization systems for various kinds of human hair waste found in municipal as well as industrial sources. The efficient and environmentally safe utilization of human hair requires identification of appropriate uses and technologies that can be adapted according to the kind of hair waste and the local circumstances of a place. For example, certain communities in China and India have been using human hair to make fertilizers, while certain communities in the USA and Japan have been making ropes from hair for applications in, for example, horse riding (vide infra).

Every material use and technology, however, also has several sociocultural and economic aspects associated with it, which often determine the adaptability of the use or the technology. Developing appropriate utilization for human hair waste in a context therefore requires considering all possible uses and technologies along with their socioeconomic and environmental impacts. While there is a large body of research literature on the biology of human hair growth [7] and hair care with its sociocultural aspects [8] and there is some research on technologies using human hair (vide infra), there is very little literature on systematic environmentally safe management of human hair waste.

This paper explores and assesses various uses of human hair from the perspective of expanding its utilization as a resource while addressing the associated solid waste and environmental problems. Historical and current uses of human hair have been reviewed including the mainstream and local/traditional uses as well as technologies that are being developed in various areas of scientific research. This includes the socioeconomic, environmental, and cultural aspects of the trade systems that have developed around some of the large scale uses. Based on this review, problems and gaps in the current human hair utilization are identified and approaches to address these are discussed. For developing human hair "waste" as a resource, various entrepreneurial considerations such as knowledge and skill requirements and potential markets are discussed. Finally, a policy framework is outlined for developing socially just and environmentally safe utilization systems for the human hair waste.

2. Methodology

Besides available literature, data on human hair uses was collected through intensive field studies involving several target groups: barbers, waste pickers, NGOs, general public and scientific researchers. The studies were conducted through informal discussions with the target group members from Delhi, Madhya Pradesh, Uttar Pradesh, Karnataka, and Maharashtra states in India during November 2011 to March 2012. Hair traders were also contacted, but they were generally quite reluctant to discuss details of the trade. The data on export and import statistics was taken from the United Nations Comtrade database. The presence of a specific hair product in the global market was assessed from online trading sites and business articles. The authenticity of information obtained through field discussions was cross-checked with people from different geographical locations as well as other available sources, and the same was attempted for data obtained from news and internet articles.

3. Uses of Human Hair

The unique properties of human hair such as its unique chemical composition, slow degradation rate, high tensile strength, thermal insulation, elastic recovery, scaly surface, and unique interactions with water and oils, along with its sociocultural roles, have led to many diverse uses. These uses also depend on the variety of hair available, varying in terms of five parameters: length, color, straightness or curliness, hair damage, and contamination.

This variation depends on the culture, ethnicity, hair styles, and the hair care practices in the region. For example, in areas with malnutrition or in areas where hair treatments such as permanent waving, dyeing, and chemical shampoos are common, hair is more damaged. Chemical contamination in hair is observed due to use of toxic dyes and chemicals in hair care, or due to the presence of toxic chemicals in the atmosphere or food chain of the area. For example, in many areas of the world where electronic waste recycling is carried out, hair is found contaminated with brominated flame retardants [9].

This section describes uses for different kinds of human hair according to the field of application. The geographical spread and historical age of the known uses is then summarized in Table 1, and the countries undertaking new research on human hair uses are listed in Table 2.

3.1. Fashion, Theatre, and Cosmetics Industry

3.1.1. Wigs, Hair Extensions, Eyelashes, Moustaches, Beards, and Other Beauty Accessories. This is one of the most ancient and currently the largest of the human hair based industries, with a constantly increasing scale due to global expansion of the fashion industry. The oldest known wigs are from 1400 B.C. Egypt, some of which are still intact today after 3400 years [10]. In the eastern countries, such products primarily catered to the theatre world, but in the west they evolved significantly with the fashion industry. This application predominantly uses good quality, long hair of

Table 1: Geographical spread, historical age, and scale of human hair uses in practice.

Use	Countries in which present	Age and scale[a] of use
Wigs, hair extensions, eyebrows, beard, and so forth	Production: India, China, Korea, Tunisia, Italy, Russia, Bangladesh, and Pakistan Market: USA, UK, Africa, Japan, China, and Italy (almost every country)	Centuries old; very large scale
Fertilizer	China, India, and USA	Centuries old (recent in USA); medium scale (few villages/towns)
Pest repellent	India, USA, and Mauritius	Centuries old; small scale
Clay reinforcement	India, Bangladesh, Syria, and Europe	Centuries old; medium scale
Oil-water separation	USA, Philippines	15 years; medium scale
Stuffing toys, furniture, mattresses, and so forth	India, USA, Hawaii, and few European countries	A century old; medium scale
Fabric making	China, India	Few centuries old; medium scale
Artwork	Past: China, England, USA, Prussia, France, Italy, and Scandinavian countries Present: China, USA	China, 1000 years, Europe, 200 years, and recent revival, 20 years; small scale
Hydrolyzed protein (HHKP)	USA, Europe	20 years; small scale
Extracting amino acids	India, China, Korea, and Europe	40 years; medium scale
Ethnomedicinal uses	China, India	Centuries old; small scale, carbonizedhair medium scale
Suturing material	Europe, India, China, and Turkey	Europe, 5 centuries, others, 50 years; very small scale
Testing material for hair care products	Europe, USA	100 years; small-medium scale
Cosmetic brushes	India, USA	40 years; small-medium scale
Hygroscope	India, China, USA, and Romania	200 years; very small scale
Nesting material for birds	USA, Europe	In nature, centuries, by humans, 50 years; small scale
Ropes	America, Japan	100 years, small scale
Musical instrument	Philippines	Centuries old, very small scale
Oil filter	China, Europe	100–50 years ago, medium scale

[a]Large scale: millions of kg; medium scale: thousands of Kg; small scale: ~100 kg.

Table 2: Countries undertaking new research on human hair uses.

New uses/areas of research	Countries where research is undergoing
Liquid fertilizers	India, USA, Korea, and Bangladesh
Concrete reinforcement	Canada, India
Pollution control	Canada, Singapore, India, Iran, Korea, Egypt, and Jordan
Molded furniture and objects	UK
Engineering polymers	Singapore, China, Japan, and India
Follicle cell cultures/tissue regeneration	Switzerland, UK, Korea, and France
Composites for superconducting systems	India, Greece, and The Netherlands
Flexible microelectrodes	China

almost all colors. In addition, hair in which all strands have surface scales in the same direction (similar to hair on the human body), known as Remy hair, is preferred because it tangles much less during working. Non-Remy hair is often used after chemically removing the outer scale containing cuticle layer. Pure Remy hair products are expensive, while those with non-Remy hair or human hair mixed with other fibers are cheaper.

3.1.2. Test Material for Hair Care Products. Human hair swatches are used as test materials for new formulations of shampoos, oils, conditioners, dyes, and so forth, (based on

information from trading sites such as http://www.alibaba.com/ and experiments reported by hair product companies and researchers). The users include hair care researchers, product manufacturers, hair stylists, and trainees in both labs and salons. These tests use hair of different colors, range of curliness, and different levels of damage.

3.1.3. For Making Cosmetic Brushes. Scales on hair can hold cosmetic powder particles and apply it uniformly on skin or a surface. Therefore, human hair is used in making cosmetic brushes [6, 11]. Almost all kinds of straight hair can be used for brushes.

3.2. Agriculture

3.2.1. As Fertilizer. Human hair is one of the highest nitrogen-containing (~16%) organic material in nature because it is predominantly made up of (nitrogen-containing) proteins. For comparison, cattle dung contains only ~0.2-0.3% nitrogen. In addition, human hair also contains sulfur, carbon, and 20 other elements essential for plants [12]. In the atmosphere, hair decomposes very slowly, but moisture and keratinolytic fungi present in soil, animal manure, and sewage sludge can degrade hair within a few months [13]. In traditional Chinese agriculture, human hair was mixed with cattle dung to prepare compost that was applied to the fields in the winter season [14, 15]. In some communities in India, hair has been used directly as fertilizer for many fruit and vegetable crops and in making organic manures [16, 17]. Recent experiments on horticulture plants show that direct application of human hair to soil provides the necessary plant nutrients for over two to three cropping seasons [18]. A company named SmartGrow has popularized the fertilizer use of human hair in the USA by selling it in the form of hair mats for potted plants. Small entrepreneurs in the USA are also promoting hair as fertilizer by packaging it in various user-friendly forms such as in tea bags [19]. By mixing human hair with cattle dung and feeding worms on the mixture, it is also possible to make good quality vermicompost within a period of about 2 months [20]. Noncomposted hair, however, has advantages than composted hair because composting can lead to some loss of nitrogen.

While the biological decomposition pathways take a few months, human hair can also be decomposed within a few hours by chemically hydrolyzing it at high temperatures in acid or base solutions. The hydrolyzed solution, which mainly consists of amino acids with some fatty acids and nucleotides, can be used as a liquid fertilizer after neutralization. Experiments using this hydrolyzate as foliar spray show enhancement of the chlorophyll content as well as biomass in spinach and wheat plants [21]. Application of the solution to soil also shows improvements in the color and size of *Amaranthus dubius* [22] and hot pepper plants [23]. Experiments on the hot pepper plants also show increased diversity of soil-intrinsic bacteria, which significantly reduces the spread of a wilt disease in these plants caused by the bacterium *Ralstonia solanacearum*. Long term impacts of this use, however, need to be assessed.

Any kind of hair without toxic contamination can be used for fertilizers. Finely shredded hair, however, is better for faster decomposition.

3.2.2. Pest Control. Human hair is also known to address problems arising from many animals as well as insect pests, although by different mechanisms. Among large animals, it has been used to repel rabbits in Mauritius [24], rodents, and wild boar in India (author's field discussions, [25]), and deer in the USA [26]. Typically, the hair is spread along the boundary of the fields/farms or near rat holes in the field. Rabbits, rodents, and wild boar find their food by sniffing, and hair supposedly causes them discomfort during sniffing by coming into their nostrils. In the case of deer, repulsion is supposedly caused by human smell emanating from the hair because hanging hair in nylon bags also works, and the technique does not seem to work well in the areas where deer are unafraid of humans. Among insects, human hair is used for deterring rhinoceros beetles in India [27, 28]. Small balls of human hair are placed at the nodes of the affected plant such as coconut tree. Beetles get tangled in the hair becoming unable to move. By using human hair mats, farmers in Florida (USA) were able to save ~$45,000 on pesticides on about 1 million plants in the year 2007 in addition to the labor savings and benefits as fertilizer [29].

3.3. Composite Materials

3.3.1. Reinforcement of Construction Materials. Due to high tensile strength and high friction coefficient, human hair has been used for reinforcing clay-based constructions. In rural areas in Uttar Pradesh and Madhya Pradesh, India (author's field discussions, [30]), Bangladesh [31], Syria [32], and in European countries [33], human hair/clay mixture (along with other binders) is used in plastering house walls, lining ovens, making wheels, and so forth. The addition of hair significantly reduces cracking and prolongs the life of these structures. Research shows that human hair reinforcement enhances the structural strength as well as the thermal insulation capacity of the clay structures [34, 35]. Although such clay-based constructions are now decreasing in rural areas, they are gaining importance in sustainable architecture.

Human hair reinforcement also reduces cracks in cement mortar caused by plastic shrinkage by as much as 92% [36] and increases the compressive strength of fly ash/cement concrete by over three times [37]. This improved fracture-resilience and strength of hair-reinforced cement and fly ash concrete is highly useful in high-pressure-bearing structures such as petroleum wells and bridges. Any kind of hair can be used in these applications.

3.3.2. Molded Furniture and Objects. A UK-based entrepreneur, Ronald Thompson [38], has developed a method for making composite materials which includes first weaving human hair into a web or mat and then adding a structural additive like resin or flexible polymer (preferably a recyclable or biodegradable material). The composite has good strength and can be used for making molded structures

such as furniture and mannequins. A similar composite with unwoven hair has also been used for making biodegradable eye glasses [39].

3.3.3. Composites for Superconducting Systems. Superconducting power equipments often use fiber-glass-based composites for cryogenic insulations. Michael et al. [40] have shown that composite laminate of human hair (and several other natural fibers) with epoxy resin has dielectric breakdown properties suitable for insulation in cryogenic systems. Compared to currently used glass-fiber composites, these composites can significantly lower the production costs of cryogenic equipments.

3.4. Pollution Control and Remediation

3.4.1. Oil-Water Separation and Oil Spill Remediation. Human hair surface has a high affinity for oils—much higher than its affinity for water [41]. This property is very useful in oil-water separation. After the pioneering work of Phillip A. McCrory from Alabama, USA [42, 43], booms and mats of human hair have been used to clean up coastal oil spills in the Philippines and the USA [44, 45]. In this method, oil can be recovered by wringing out the hair, which then can be reused up to 100 times—advantages not present in other oil spill remediation methods. With this method, up to 98% of the spilled oil can be recovered. The oily hair can then be used to grow oyster mushrooms [46], which decompose the oil. The hair then left can be composted. Human hair can also separate emulsified oil in water, which is very expensive to clean by other methods [41]. This property can greatly help in cleaning effluent from industries such as oil refineries. Any kind of hair can be used in these applications (except with toxic contamination, which can contaminate the water body).

3.4.2. Removing Phenols, Aldehydes, Dyes, and Heavy Metal Pollutants from Water. Human hair absorbs several chemicals from aqueous solutions. Experiments show that human hair can absorb organic pollutants such as formaldehyde [47] and phenol [48], and heavy metals such as mercury (Hg), copper (Cu), cadmium (Cd), and silver (Ag) from aqueous solution [49, 50]. The capacity for metal absorption can be enhanced by pretreating the hair with an alkali. Powdered human hair has good absorptive capacity for Ni (II) and Cr (VI) ions at acidic pHs [51], and partially burned human hair [52] shows selective absorption of mercury (Hg^{2+}) and silver (Ag^{+}) ions over cobalt (Co^{2+}), copper (Cu^{2+}), and iron (Fe^{3+}). Thus, human hair can be a low cost absorbent for purification of polluted waters. The recycling/disposal of contaminated hair, however, can become a problem. Partial recovery of absorbed metals from the hair has been explored [49], but further research is needed to develop recovery/recycling methods for such chemicals from the contaminated hair.

3.5. Pharmaceuticals and Biomedical Applications

3.5.1. Pharmaceuticals. Human hair proteins typically contain 20 essential amino acids, which can be extracted by complete hydrolysis of hair [7]. Some of the amino acids obtained in good yield from human hair are L-cysteine, L-leucine, L-isoleucine, and L-valine. L-cysteine and its chemical derivatives are used in many cosmetics and pharmaceutical formulations. For example, L-cysteine is used for permanent wave lotions and wound healing formulations, while one of its derivatives, N-acetyl L-cysteine (NAC) [53], is used to treat conditions such as chest congestions and acetaminophen poisoning. Hair from certain demographic regions is better for extracting certain amino acids. For example, black hair from Asia has more cysteine than blonde hair. In addition, hair that is chemically not altered by any styling treatment is better, because some of these treatments can change the chemical structure of the hair. For example, increasing trend of permanent waving in some parts in China has made cysteine extraction from this hair difficult [54].

3.5.2. Hydrolyzed Hair Keratin. A mixture of amino acids and polypeptides obtained by the hydrolysis of keratin protein from human hair, known as hydrolyzed human hair keratin protein (HHKP), is used in hair care products by many companies [55, 56]. It is reported to repair hair damage caused by various hair styling treatments supposedly because its constituents are similar to the native hair protein. HHKP extraction requires uncontaminated hair.

3.5.3. Ethnomedicinal Uses. Several cultures have been using human hair for preparing traditional medicines. Carbonized human hair (Chinese: *Xuè Yú Tán*, Latin: *Crinis carbonisatus*) has been used in Traditional Chinese Medicine [57] for treating hemorrhage, burns, wounds, and scars. It is also used in veterinary medicine to stop bleeding and to promote urination [58]. In rural communities in Chhattisgarh, India [17], hair ash is applied to open wounds for immediate pain relief as well as long term recovery. In addition, these communities use formulations made from powdered hair, hair ash, and hair decoction for the treatment of mouth ulcers, ringworm, and blisters due to burns. Another ethnomedicinal study in India [59] has revealed therapies using human hair for treatments of anemia, asthma, urinary calculus, piles, rat bite poisoning, foot sprains, sexual problems, and childbirth pain. The quality and purity of hair is of essence in these preparations.

3.5.4. Suturing Material in Surgery. Human hair has sufficiently high strength for use as suture in most surgeries. It is relatively easy to tie knots with and is noninfectious (because of its slow decomposition rate and high compatibility with the human body). Its use as suture was known in Europe in the middle ages [60]. Studies have now established the potential of human hair sutures in cataract and conjunctival wound repair surgeries [61, 62], general surgeries on humans and animals [63], and in microsurgery [64]. It can be easily sterilized by autoclaving. Long, undamaged hair of medium thickness (not too coarse or too thin) is best for suturing.

3.5.5. Keratin-Based Engineering Biomaterials. In 2002, Nakamura et al. [65] developed the Shindai method to extract

proteins rapidly and efficiently from human hair, opening possibilities of reengineering human hair proteins into new materials. Based on this method, many materials with novel properties have been developed such as hair protein based thin films [66], hair protein gellan chitosan hybrid fibers [67], and protein scaffolds and hydrogels for tissue engineering [68, 69]. These materials have several potential applications in bioengineering and medical science such as for wound dressing and soft tissue regeneration with the advantage of good biocompatibility with the human body. Investigations on effects of these materials in surgical applications are under progress.

3.5.6. Human Hair Follicle Cell Cultures and Tissue Regeneration. Biomedical studies show that certain cells from human hair follicles such as outer root sheath cells also are useful in wound treatments [70], autologous grafting of chronic wounds [71], and treatment of alopecia [72]. The follicles are collected from fallen hair or hair plucked from volunteers. Therefore, this application is not likely to utilize much of the hair waste.

3.5.7. Flexible Microelectrodes. Human hair by itself is not a good conductor of electricity, but Xu et al. [73] from China have developed a human hair microelectrode by coating its surface with an ultrathin layer of gold. Currently used carbon fiber microelectrodes have good electrical conductivity, chemical stability, and low cost but are brittle and have weak signal strength and limited biocompatibility. The human hair microelectrode is flexible and its signal strength can be tailored by changing the hair length. The gold coating is chemically stable and the electrode is likely to be compatible with biological systems. In addition, these electrodes can also be useful as microsensors for small biomolecules. Further experiments are needed to test their efficacy in various biological systems.

3.6. Food Industry. Many amino acids obtained from human hair such as L-cysteine are also used in the food industry as leavening agent for pizza dough and doughnuts, for artificial meat flavor, in nutritional supplements, and so forth. The use of human hair derived amino acids in the food industry, however, is a big source of concern in many countries (vide infra).

3.7. Scientific Instrumentation. Human hair expands in length on absorbing moisture, and this expansion is reversible. This property was used by Horace-Benedict de Saussure in 1783 to make a hair hygrometer for humidity measurements. Since then, the instrument has undergone improvements and modifications in design [74, 75]. Although more sophisticated electronic instruments are now available for more precise measurements, hair hygrometers are still cheap and simple for reasonably good estimations of humidity and are still used in many metrological stations in the world. This application requires long hair (~12 inches or longer).

3.8. Textiles, Fiber Stuffing, and Other Artifacts

3.8.1. Stuffing Toys, Mattresses, and Other Household Items. Due to its elastic and cushiony nature and good thermal insulation properties, human hair has been used to stuff household items such as hair-pin cushions and toys in Hawaii and the USA [76, 77]and toys, furniture, mattresses, quilts, jackets, and so forth, in India ([6], author's field discussions). In pin cushions, natural oil of the hair prevents the pins and needles from rusting [76]. For toys and mattress stuffing, human hair is usually mixed with cotton or other fibers (author's field discussions).

3.8.2. Fabrics. High thermal insulation, elasticity, and good tensile strength also make human hair useful for making various kinds of fabrics. In Arunachal Pradesh, India, people have traditionally been making fabrics by mixing human hair with yak hair, nettle fiber, and cotton [78]. In China, human hair, yak hair, and cotton are used to make interlining cloth for coats and jackets [79]. In these applications, mostly cotton yarn is used as warp and the hair is used as weft. Human hair blended with animal fibers is used for making blankets in Panipat, India. A company al. Kishore's (Chennai, India) has also started making purely human hair fabric and clothing. Making felt from human hair is more difficult than from animal hair, but it is made by many for use as doormats, thermal padding of furniture, artwork, and so forth. A Serbian artist produced 1200 sq. m. of felt from human hair in 2009 [80].

3.8.3. Oil Filters. Tightly woven human hair cloths were used in the 1920s as filters for heavy oils in refineries and distilleries because these processes involved high pressure that many natural fibers could not withstand [81]. Hair cloths, by contrast, were tough and almost untearable. Later, synthetic fibers with higher tensile strength and smaller diameters became available. Filters of these fibers could filter even smaller particles and therefore replaced the human hair filters.

3.8.4. Ropes. Due to good tensile strength, human hair has been used to make ropes in many cultures, for example, to lift heavy beams and bells in the construction of Japanese temples [82] and for household purposes by Native Americans [83]. These ropes are still valued for horse riding [84].

3.9. Artwork. Two art traditions evolved in the world around human hair as the key material. The first—hair embroidery (called *Moxiu* in Chinese)—flourished in China between the 7th and 13th centuries, when women made images of Buddha with their own hair [85]. This art revived again in the late 20th centuries and now has surpassed its past in color and variety. Earlier, natural shades of hair were used, but now dyed hair is also used. The tradition has even developed a rich school of portrait embroidery [86].

The second tradition—hairwork—evolved in the 19th century Scandinavian countries and then spread to England and America [87, 88]. Hairwork included intricate jewelry,

flowers, buttons, brooches, and so forth, made of human hair with gold and resins. It also included the craft of hair embroidery. Dissolved hair and finely chopped hair mixed with oil were used as paint. The 1853 Crystal Palace Exposition in New York included a full line of hairwork jewellery, buttons, flowers, and even a tea set made completely of hair. Socially, hairwork pieces were mainly associated with special affection such as between spouses and in memories of a dead person (with hairwork piece made from the deceased person's hair). Increasing symbolism of hairwork with death and mourning led to fading of this tradition by the early 20th century; however, recently, there is increasing interest in reviving this art and a society has been established to connect and promote hairwork artists in the world [89].

3.10. Miscellaneous Uses. Human hair is placed with other fibers as nesting material to increase breeding of birds in places where bird populations are declining. Long fibers can entangle and cause injuries to the birds; therefore, short hair (3 inches or less) is recommended for the use. A stringed musical instrument named "gitgit" is also made using human hair as strings [90].

4. Chains of Value Addition in the Human Hair Trade

Some of the uses discussed above have developed very elaborate chains of value addition for human hair, starting from collection to processing to marketing of various products. These systems have been largely shaped by the sources of hair, the actors involved, kind of processing required, nature and scale of distribution and markets, and the consumers concerns and preferences. This section highlights some of the key features of these socioeconomic systems.

4.1. Collection Systems. Based on different sources, five kinds of collection systems are observed for human hair.

Barbers and Hair Stylists' Shops. Barber shops are one of the most convenient sources of the hair obtained from haircuts. In many countries (India, China, etc.), these shops predominantly collect long hair (>6 inches), usually obtained from women's haircut or tonsuring, because of its higher market value for the wig trade. Short hair is mostly thrown away. At some places such as New Delhi (author, discussions with barbers) and Chennai [91] in India, short hair is also collected at very low price or for free for making quilts, blankets, amino acids, fertilizers, and so forth.

Special Religious Places Like Tirupati Temple. At certain religious places such as Tirupati Balaji temple in Andhra Pradesh and the city of Varanasi in India, a large number of people get tonsured as part of their religious practices [92]. The hair available here is of good quality because a large fraction of the visitors there come from rural areas who maintain their hair with natural oils, clay, and so forth. In addition, since women also get tonsured in these places, long hair is available in large amounts. Due to its high value, this hair is usually auctioned by the temple administrations or the barbers.

Hair Harvesting. In several regions of the world, many (usually poor) people collect and sell their own hair. This collection is in two forms: growing the hair long and cutting it and collecting the fallen hair during daily combings; the first case fetching more money. Harvesting long hair was well known in the 19th century in Prussia, England, France, Germany, Italy, and Romania [93, 94], where hair dealers would go to villages at annual fairs. Young girls would tend their hair year round and sell their tresses at the fairs in exchange of a handkerchief, a ribbon, or some money. By the last part of the 20th century, this business spread via Poland to Ukraine and Russia [95]. In parallel, similar collections also developed in India and other South Asian countries [96]. Currently, individuals can also sell their hair through several internet sites, though this trend is more prevalent in the USA and European countries.

The collection of fallen hair is known since the Victorian era when hair was collected for hairwork. In Indian villages, women collected their own hair for plastering ovens and walls (author, field discussions, Delhi and Madhya Pradesh). In many of these villages and urban slums, this hair is also sold to travelling traders in exchange of toys, hair accessories, and so forth [97, 98].

Trash Sorting and Scavenging. In many places (usually urban areas), where the fallen hair is not formally collected, it is thrown away in the household trash, dumpsters, or drains. This hair is then scavenged by waste pickers who collect and clean it. This practice is known since the mid-19th century Italy, where ragpickers scavenged for hair thrown away in drains for supply to America [88]. Currently, in many Indian cities including New Delhi, Ghaziabad, Ahmedabad, Vellore, Bangalore (author's filed discussions, [98]), ragpickers collect hair out of trash coming from households, salons, hospitals, and so forth.

Charities. In the past century, several charity organizations have started collecting human hair donations from salons, school students, individuals, and so forth, specifically towards social causes such as hair tresses for cancer patients suffering from hair loss and oil spill remediation. Organizations, namely, Wigs for kids, St. Baldrick's Foundation, Locks of Love (mostly based in USA) are a few collecting hair for patients suffering from hair loss and Matter of Trust collects hair for oil spill remediation. Most important feature of this system is that the hair is given for specific use without any money exchange involved.

None of these is a standardized system and exact collection mechanisms vary from one location to another, but two key features distinguish these systems: the intentions of the hair donors in parting with their hair and the actors involved in the collection. Table 3 summarizes donors' intentions and the critical actors in the systems of collection described above. In collection via salons, trash scavenging, and religious tonsures, the donors often have no information or concern about the fate of hair, but, in hair harvesting and donations,

Table 3: The intentions of donors and the critical driving agents in various human hair collection systems.

System of collection	Donor's intention	Critical agents/stakeholders in collection
Salons	To get rid of hair	Barbers/hair collectors
Religious places like Tirupati temple	To remove/to offer the hair	Barbers/religious authorities
Hair harvesting	To earn money	Donor, hair collectors
Trash scavenging	No information or concern	Ragpickers/hair collectors
Charities (for wigs and oil spills)	For social good	Charity organization

donors actively participate in the collection process. The critical collectors range from barbers in the salon collection to ragpickers in trash scavenging. These collectors then sell the hair either directly to the hair processing units or to the large hair traders who supply it to the processing units. These systems also show that both economic as well as non-economic motives can drive the hair collection and a wide variety of actors can be involved in the process.

Among these systems, trash scavenging particularly is of concern because it involves several hazards. The ragpickers mostly work with bare hands and often get injuries and develop health problems. This system, however, also provides livelihood to large populations in many countries who have no other opportunities available to them. Therefore, there is a need to upgrade and improve the working conditions of the people in this system while maintaining their livelihoods.

In addition, several unjust hair collection practices have also been observed involving forceful shaving of hair from poor and helpless people and from dead bodies. During the Second World War, hair was shaved from prisoners and dead bodies in the German concentration camps to make war items such as felt and fabric [99]. In poor neighborhoods in India, hair collectors would abduct women, shave off their hair, and release them [98]; sometimes the traders get the hair by paying women's husbands or family members. In Eastern Europe, prisoners and psychiatric patients are forcefully shaved by the institutions' staffs, who make money by selling the hair [100]. In spite of public reports, these acts have not been regulated. Although such practices are not present everywhere and in every time, stopping these practices is crucial for a socially just human hair trade.

4.2. Storage and Processing. After collection, proper cleaning and storage is crucial to remove any moisture, pathogens, oil, and biological or chemical waste to retain the shelf life of the hair and prevent related disease or environmental hazard. Further processing is needed according to the targeted products or applications. In small scale uses, all the processing is done by the users only. For example, in ethnic medicinal system, the barbers would supply good quality hair for the medicines directly to the medical practitioner who would then process it further [17]. In large scale industries, processing involves elaborate systems with large number of actors.

Detailed description of the processing practices and their prevalence is not possible here due to limited information, but author's visits to processing units in Delhi and online reports by others [101] reveal some general practices in these places.

Separating Hair from Other Waste. Depending on the source, the collected hair often has other wastes such as cotton, blades, and household waste, which are first separated—in almost all cases—manually by several workers. This can be the case even for the sorted hair obtained from ragpickers or travelling hair collectors (sometimes the collectors intentionally add other stuff to add weight).

Washing. After sorting, the hair is washed. In the hairwork tradition, the hair was boiled in soda water for 15 minutes before use [102]. These days washing is done in water with caustic soda, soap, shampoo, detergents, or chemicals.

Drying. The hair is then dried under sun, in oven, or with hot air blowers. After drying, the hair can be stored without any concern for decay or odor.

Sorting. The hair is then sorted according to length, color, and quality. For example, strands of white hair are removed from a bunch of black hair.

Untangling. The long hair is untangled and then weaved.

Most of these processes have developed around the wig and hair extension industry but are common for other uses as well. Some steps vary according to the product. For example, the non-Remy hair in the wig industry is washed in acid to remove the tangling problem. Untangling is not needed for amino acid and pharmaceuticals production. For such applications, hair is chopped into fine pieces and then processed chemically [101].

In contrast to the collection systems, which are driven by large number of independent individuals, most of these processing units are run by enterprises managing the entire chain of processing steps except the collection. Most of these enterprises are large private companies; however, some smaller enterprises and workers' cooperatives also exist [5, 103]. A lot of these units have developed in poor areas of the world because most of the processing is labor intensive. As a result, these industries also provide large scale employment in these areas.

As mentioned in Section 1, large scale expansion of human hair industry has also been a source of environmental and health problems. In addition to waste hair, other processing waste has also caused problems in some cases. In a facility manufacturing amino acids from human hair near Tirupati temple (Andhra Pradesh), effluent discharges caused significant ground water pollution [104]. Protests against the pollution led to closing of the facility (personal communications with Gowd, S. S., 2012). To address these,

some of the enterprises have attempted safer modes of production, such as asking donors to provide cleaner or sorted hair, providing masks to workers, and setting waste treatment plants. In some wigs and hair extension industries in Delhi, the low quality left-over hair is sent to blanket-making industries in Panipat (author's field discussions). Some of the solutions, however, have not worked in places. For example, many workers find masks inconvenient and do not use them [5]. These cases underline the need for a broader systemic thinking incorporating the lessons learned from these cases to develop safe practices of hair processing and waste management while ensuring well-being of the workers.

4.3. Markets, Consumer Preferences, and Regulations. The global markets for human hair products have undergone large dynamics and this dynamics has varied according to the social and cultural perceptions about the product and its competing materials and products. Concerns about the product safety and trade regulations have also affected the markets for some of the products. The trade in unprocessed human hair was almost unrestricted until the mid-20th century. China banned the import of unprocessed human hair in 2002 due to increasing environmental problems [105].

The trade of wigs and hair extension has been fully unrestricted. The largest consumers in early 20th century—Europe and America—manufactured the wigs locally although with largely imported hair. Now, China, Hong Kong, Indonesia, and Italy are exporting finished products and the USA, UK, Japan, France, and Korea are the largest markets [3]. The coming of (cheaper) synthetic fibers in the 1970s reduced the demand for these human hair products [106]. However, better looks as well as workability of the natural hair helped it regain the markets by the 1980s. Increasing scale of trade has reduced the prices of natural hair products making these affordable for more people. The hair from India is in high demand because of much less chemicals and synthetic hair care products used on it and a large part if it coming from temples, which often is seen as a positive association. European and Russian hair is in demand because of its light color which can be easily dyed into various colors.

Several kinds of consumer concerns have affected the markets of wigs, hair extensions, and so forth. The first is about the safety in using hair treated with strong chemicals during processing because these cause allergies and skin problems to some users. Secondly, consumers do not prefer hair that is unethically sourced. The third involves religious and cultural beliefs specific to some societies. For example, in 2004, objections were raised within the Jewish community in the USA about the use of human hair wigs associated with temples in India and idol worship [107]. This controversy led to large scale public burning of natural hair wigs in the New York city and caused a significant blow to wig sales. After several debates and investigations, some Jewish groups disagreed with the objections, while some groups adhered to ban on natural hair wigs [108, 109].

Marketing and packaging strategies have promoted some of the human hair products in new markets. Carbonized human hair used in traditional medicines in China gained international markets due to increasing recognition of Traditional Chinese Medicine. In addition, marketing it as tea, single-use smaller packaging (e.g., 10 g), and using it in new formulations such as wound healing creams contributed to its increased use. Similarly, the idea of using human hair in agriculture was repulsive to many farmers in the USA. However, marketing in user-friendly forms such as mats by SmartGrow (vide supra) and highlighting of benign nature of the product and its advantages increased its acceptability [29]. Because of lack of extensive and inexpensive collection in the USA, however, the hair is largely imported from China and India [110].

The human hair derived chemicals in food products and cosmetics, while traded at large scales, have been a source of worldwide concerns and regulations. In 1976, the European Union prohibited the use of cosmetics having products of human origin (Cosmetic directive 76/768/EEC, Entry 416, Annex II), but the European Cosmetic Toiletry and Perfumery Association requested for modification in this directive to allow certain human hair derived materials in cosmetics. In 2005, Scientific Committee on Consumer Products of European Commission adopted an opinion SCCP/0894/05, permitting amino acids from human hair in cosmetics and non-food products provided they have been extracted under specific conditions [by hydrolysis of human hair with HCl (>20% during the whole process) for at least 6 hours at 100°C], to eliminate any health safety concern for external applications on human body. The European Union explicitly prohibited the use of amino acid L-cysteine in food products by the directive 2000/63/EC. Many religious communities have prohibited all human hair based products for food consumption because of their human origin. Apart from these regulations, a related and bigger concern has been the coming of food products in the markets, such as soy sauce made from human hair in China, sold without revealing the source of ingredients and often prepared in very unhygienic conditions [111]. Following media revelation of this practice, Chinese government banned the production of food items from human hair. These cases highlight the need for vigilance about safe processing and informed use of human hair products in food and cosmetics.

In summary, markets for many human hair products have expanded significantly in spite of several competing products. There is a large scope of expanding its markets provided consumer concerns are addressed and harmful practices in trade are checked.

5. Addressing the Concerns and Gaps in the Current Scenario

The concerns in the human hair trade discussed above relate to the means of collection, the working conditions at the hair processing industries, waste disposal, and the products safety for the consumers. In addition, packaging and post-consumer waste generated from the human hair products is another issue that needs to be addressed. The disposal of these products after use can create solid waste problems of a similar

nature or sometimes much worse than the original material. This section discusses possible solutions to these problems.

5.1. The Gaps in the Collection, Processing, and Trading Systems. Although addressing the concerns in the trading systems need different strategies according to the locations, certain broad guidelines can help in achieving these goals.

Ensuring safe and ethical collection requires multidirectional approaches. Governments must stop forceful cutting or shaving of hair in public, prisons, mental health institutions, and so forth. Source separation of human hair from other waste needs to be encouraged at barber shops and households to reduce hazards to ragpickers and workers in the hair processing units. This can be done by spreading awareness about reusability of hair and creating more financial or other incentives such as those existing in the hair harvesting systems.

The processing units must ensure safe working conditions, environmental safety around the units, and product safety for the consumers. Cleaning and drying the hair soon after collection and storing it in dry and enclosed places would minimize the odor and hair dust problems. In most cases, cleaning and disinfection of hair can be accomplished by washing in hot water with soap or soda without any strong chemicals, which will reduce toxic effluents. Use of herbal soaps can further reduce the chemical discharges. Acids or bases, if used, must be neutralized and the water should be treated in an effluent treatment unit before discharging it. Hair waste from most of these units can be used as fertilizer. Hair of length ~1 cm or more can also be used in mud and concrete reinforcements. The waste protein solutions produced in amino acid extracting units can also be used as soil nutrient after proper pH control.

In terms of packaging, human hair fundamentally has no special requirement because, firstly, hair is solid, and, secondly, cleaned and well-dried hair is stable in atmospheric conditions. Consumers in many places are also asking for ecofriendly packaging of cosmetic products including the human hair products [112]. Therefore, use of biodegradable or reusable packaging at minimal necessary level must be promoted for human hair products.

Consumer concerns about human hair products have two aspects. First is the safety of using human hair itself in various products, which can be assessed by undertaking systematic research on the products. An example is the approach undertaken by the European Union on the use of human hair derived amino acids in cosmetics. Second is the contamination or hazards in the products originating from the hair's source, collection method, or processing conditions. To identify such hazards in the products, simple tests should be developed for contaminants and product quality that can be conveniently conducted by consumers and standard enforcement agencies. In addition, standard protocols can be developed for safe hair processing for each use or product.

Transparency in the supply chains is also helpful in addressing many of the concerns; that is, the consumer should be able to know how the hair has been sourced and processed. Enterprises that manage the full operations starting from the collection to processing to sales are often more traceable, and these should be encouraged. Cooperatives of hair collectors, empowered with skills and financing to operate the complete chains of value addition, can also be an option for socially just and traceable systems.

5.2. Recycling of "Post-Consumer" Human Hair Waste. Every use of human hair does not reduce the human hair waste because, in some uses, the disposal of the hair after use can bring it back into waste streams. For example, even though wigs and hair extensions use human hair at large scale, the hair is not consumed during use, after which it is again thrown away in the solid waste. On the other hand, the fertilizer use decomposes the hair and returns its elements back to the cycles of nature.

In terms of material flow, human hair uses can be broadly classified in three categories illustrated in Figure 1. For simplicity, these categories are called Type 1, 2, and 3 uses. In Type 1 uses, hair decomposes during processing or use and eventually becomes a part of the natural biological cycle. This category predominantly includes the agricultural uses, extraction of amino acids, uses in medicines, cosmetics, and sutures (after proper decomposition with biomedical waste).

Type 2 uses are those in which the hair remains intact during use and there is possibility of further recycling or reusing the hair after use for the same or different applications. This category includes wigs and hair extensions, toys and mattress stuffing, ropes, and so forth. Products such as hair fabric and hair embroidery pieces have human hair blended with other fibers/materials. These products can also be in Type 2 category but the possible recycling pathways would depend upon the other material(s) contained in the products. For example, hair fabric containing only human hair, yak hair, and cotton can be composted, but fabrics also containing synthetic fibers such as polyester are difficult to compost. Recycling such fabric would require the fibers to be separated.

Type 3 uses would neither decay the hair nor leave it intact for safe reuse or recycling. These are the applications that involve either contamination of the hair with toxic chemical or irreversible blending with certain non-biodegradable or ecologically unsafe materials. Hair contaminated with toxic organic pollutants is one such case. Other such use would be human hair composites with non-biodegradable resin. Recycling or safe disposal of these products require further processing to remove the specific contamination or separation of the other materials. For example, hair composites with non-biodegradable resin would need a method to separate the two materials or a method for safe decomposition such as combustion at very high temperatures to ensure safe destruction.

Reducing total human hair waste requires different approaches for each of the three categories. Type 1 uses must be promoted to ensure pathways which decompose and return the hair back to nature in healthy ways. For Type 2 uses, buy-back and reuse systems for the hair need to be developed so that these products do not end up in landfills. Such buy-back centers can be developed at barber shops, wig shops or as separate waste hair shops. Type 3 uses need research

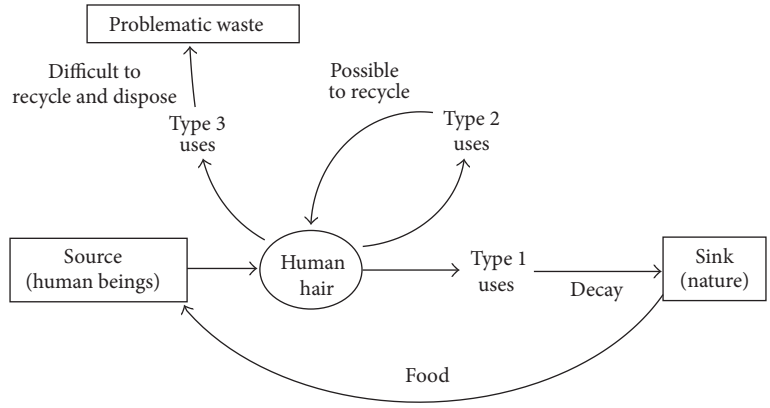

Figure 1: Flow of human hair as material in various possible uses.

and development of methods that can be adopted widely to ensure either safe decomposition or recycling of hair and other constituent materials.

6. Developing a Policy Framework for Human Hair Utilization

Even though significant human hair trade has developed in many parts of the world, the percent share of the available hair that is currently used is small. By assuming that every individual on average sheds ~100 g of hair annually by haircuts and during combings, annual hair harvests from India alone, with a population of ~1.2 billion (Census of India, 2011), amounts to ~120 million kg (No exact data is available, but hair growth for an adult is about 6 inch ~100 gm per annum. Average over entire population is likely to be slightly lower because of less hair in babies and old people but will be within 50% of this number.) In addition, there is similar amount of hair left from past years that has not decomposed and the post-consumer hair waste from wigs, stuffing, and so forth. The net export of human hair and its products from India was only ~1 million kg in the year 2010 (vide supra), and the local consumption in the country is much smaller. Therefore, current utilization even in India, with a very strong hair trade, is only about 1-2%. Such large amount of unused hair presents a significant potential for developing its uses in almost all parts of the world.

The availability of human hair in almost every city or town in the world is sufficient to support medium-sized operations of most of the uses. For example, a small town with a population of 100,000 generates an estimated annual hair harvest of ~10,000 kg, whereas large cities like New Delhi, with population of ~16 million (Census of India, 2011), generate ~1.6 million kg annually—sufficient for many small to large scale operations.

Expanding human hair utilization to new locations needs a policy framework that must incorporate two simultaneous tasks: ensuring environmental and social well-being and building necessary support system for developing local as well as large scale uses. A support system would be based upon the knowledge, skill, and technology inputs needed for the uses and the market potential for the uses. This section first discusses the considerations such as inputs and market potential for promoting various uses. Then a policy framework is outlined that can incorporate the environmental and social justice with market expansion.

6.1. Knowledge, Skills, and Technology Inputs. The uses of human hair span a wide variety of knowledge, skills, and technology needs. Based on these requirements, the uses can be categorized into three broad groups: K-centered, KS-intensive, and KST-intensive. K-centered uses only require basic knowledge and understanding about the use but not much skills and technology, for example, fertilizer, pest repellants, and so forth. Promoting these uses need only knowledge dissemination about the advantages and appropriate method(s) of the use.

KS-intensive uses would require knowledge as well as skills but not much technological input. Weaving a good quality hair cloth or doing hair embroidery requires intricate skills in the art. These uses do not require extensive technology or capital investment as they have been practiced in many rural and tribal societies for long. Developing these uses would require skill development through training programs.

KST-intensive uses would need knowledge, skills, and access to technology. Adopting these uses would require development of technical manpower as well as resources. For example, making hair-hydrolyzed proteins and engineering biomaterials are technologically intensive processes and require knowledge, skill, as well as finances to afford the technology.

This categorization is not rigid because innovations can change the skill, knowledge, or technology requirements for a use. Automation of many of the K-centered or KS-intensive uses can increase the requirements of technology and change the kind for knowledge or skills needed. For example, Smart-Grow Company (vide supra) introduced human hair mats for fertilizers and incorporated weaving technology in the production, which added skill and technology requirements to the use. Sometimes a technology can also become so cheap or simple that even a KST-intensive use can become widely accessible.

Table 4: Key attributes of various human hair uses.

Use	Kind of hair required	Knowledge/Skills/ Technology required[a]	Post-Consumer reusability/recyclability[b]	Potential users/markets	Nature of market
Wigs, Hair extensions, and so forth	Long, undamaged	KS	Type 2	Fashion-conscious individuals, patients suffering hair loss	High value, high volume
Soil nutrient (without chemical processing)	Any kind, without toxic contamination	K	Type 1	Farmers, gardeners, and households having garden/potted plants	Low value, high volume, and high need
Soil nutrient (chemically decomposed hair)	Any kind, without toxic contamination	KST	Type 1	Farmers, gardeners, and households having garden/potted plants	Low value, high volume, and high need
Pest repellent	Any kind	K	Type 1 because decays in nature eventually	Farmers, gardeners, and households having garden/potted plants	Low value, high volume, and high need
Stuffing of mattresses, coats, toys, and so forth	Any kind, except very small ones (<1 inch)	K	Type 1	Furniture makers, toy makers, artists, and so forth	Low value, high volume, and high need
Hair fabric, interlining cloth, and felt	Any kind except small ones (<2 inch)	KS	Type 2	Coat tailors, garment enterprises, artists, and producers of mats	Medium/high value, low volume
Ropes	Any kind except small ones (<2 inch)	KS	Type 2	Anyone	Medium value, low volume
Hair embroidery, hairwork	Long, smooth hair	KS	Type 2; Type 3, if hair embedded in a resin	Artists, religious institutions, art connoisseurs, home decorators	High value, medium volume
Suturing in surgery	Long, undamaged hair of medium thickness	KS	Type 1 if decomposed along with biomedical waste	Medical personnel	Medium/high value, low volume
Reinforcement of construction materials	Any kind	K	Type 1, clay reinforcement; Type 3, concrete reinforcement	Households, architects, designers, and construction workers	Low value, high volume, and high need
Oil spill remediation, effluent water treatment	Any kind, except very small (<1 inch)	K	Type 1 if coupled with mushroom growing and composting and without toxic contamination	Petroleum industry, oil refineries, sewage treatment, and water supply departments	Low value, high volume, and high need
Hair-hydrolyzed protein	Any kind	KST	Type 1	Hair care industry	High value, low volume
Extracting amino acids	Any kind except contaminated and chemically treated hair	KST	Type 1	Agriculture, food processing, and pharmaceutical industries	Medium/low value, high volume
Traditional Medicine	Uncontaminated, undamaged hair	KS	Type 1	Traditional medicine practitioners, patients	Low value, low volume, and high need
Testing material for hair care products	All kinds	According to the experiments	Type 3	Hair care industry	Medium value, low volume
Cosmetic brushes	Undamaged hair	KST	Type 3	Fashion conscious people (mostly women), theatre personnel	Medium value, low volume
Hair hygroscope	Long, undamaged hair (>12 inch)	KST	Type 2	Meteorologist, Scientific institutions	Medium value, low volume

Table 4: Continued.

Use	Kind of hair required	Knowledge/Skills/ Technology required[a]	Post-Consumer reusability/recyclability[b]	Potential users/markets	Nature of market
Nesting material for birds	Any kind but ~3 inch or smaller	K	Type 1 as it decay in nature eventually	Environmentalists, horticulturists, and gardeners	Low value, low volume
Removing dyes, other pollutants	Any kind	KST	Type 3	Industries having effluents, pollution control organizations	Low value, high volume
Board and furniture	Any kind	KST	Type 3, compostable if resin is biodegradable	Furniture makers, fabric shops for mannequins	Medium value, high volume
Engineering biomaterials	Any kind, uncontaminated	KST	Type 1	Medical doctors, researchers	High value, low volume
Composites as dielectric	Any kind	KST	Type 3	Electrical power sector, scientific institutions	High value, low volume
Flexible microelectrodes	Any kind, except small (<1 inch)	KST	Type 2	Scientific Institutions	High value, low volume

[a]Based on Section 6.1.
[b]Based on Section 5.2.

6.2. Markets and Need Areas. Market potential for human hair products depends on potential need areas, the economic feasibility, and advantages of the hair products in relation to its competing materials/products. There are several need areas in which human hair use can have a large impact. A single most important area is agriculture. With the approximate composition of ~16.5% nitrogen and assuming 50% of this amount recoverable by direct application in the soil (to account for nitrogen loss as gaseous oxides during decay), ~120 million kg of hair shed annually in India (vide supra) is equivalent to 9.6 million kg of nitrogen and ~20 million kg of urea. This use can significantly reduce the pressure on the petrochemical sector. Further, it is more sustainable because human hair is a renewable and locally sourceable resource as compared to the fossil-fuel-derived urea.

Pollution control, low cost medicines, sutures, and construction reinforcement are other key need areas in many countries in which human hair can be effectively used at large scales. For example, while many surgical sutures are available in the markets, sterilized human hair is a safe, locally available, and low cost option for many poor areas as well as for disaster times when large amount of medical supplies are needed at short notice.

Economic feasibility of hair products in the market depends on the scale of use, the value, and presence of potential consumers in a region. Uses such as wigs and artwork are high value markets and are economically feasible even if volume of sale is relatively low. On the other hand, uses such as fertilizer, pest repellant, stuffing of mattresses, and construction reinforcement have low value markets but can be economically feasible because of their high volume of usage.

6.3. Policy Framework. Based on above discussion, Table 4 lists five key attributes for the hair uses. The kind of hair needed and the knowledge, skills, and technology requirements determine the feasibility of a use in a region. The post-consumer recyclability type indicates the kind of efforts needed to prevent further solid waste problems, while potential users and markets would determine the scope of the use.

Based on these attributes and the discussion in Section 5.2, the following policy guidelines emerge.

(i) Legislations must be passed and enforced to stop forceful or unethical sourcing of hair.

(ii) Standards need to be developed for cleaning, drying, and packaging of human hair that minimize the chemical use and waste production and ensure environmental safety while maintaining the product quality.

(iii) Multiple uses need to be developed at each location to utilize different kinds of hair efficiently. Hair waste and other processing waste from the hair industries should be used in other possible applications, as detailed above.

(iv) Type 1, K-centered, high-volume, and high-need uses are environmentally the safest and easiest to promote. Knowledge about these uses should be widely disseminated.

(v) Buy-back systems need to be developed for Type 2 uses, particularly with high volume markets.

(vi) Type 3 uses, particularly with high-volume markets, should be promoted only after appropriate methodology for decay or recycling of the product is formulated.

(vii) Research on utilization and decay of contaminated hair and Type 3 products must be promoted.

(viii) Training and technical support should be provided for KS- and KST-intensive uses with focus on environmental and human health safety.

(ix) High value products should be promoted to economically support the low value products and thus the overall hair utilization cycle.

Several stakeholders can contribute in evolving such a framework. Local governments and municipal bodies can facilitate the hair collection systems and business ventures, which will reduce their cost of solid waste management as well as the environmental burden on the area. National governments need to develop legislation for ethical collection and environmentally safe processing of hair. Governments should particularly help in promoting uses of public importance such as agriculture, oil spill control, construction reinforcements, and medical applications. Academic institutions can undertake research on safety issues of human hair uses and help in developing standards. These institutions, with the assistance of community experts, can also help in training people in the hair industry and the public about its uses and appropriate technologies. Increased awareness about the advantages of human hair in various areas can also make the public a stakeholder in this process. This awareness while reducing the stigma attached to human hair as a waste will also encourage local uses and innovations in the products and technologies, as well as in the institutions of hair trade.

7. Conclusions

This study has shown that human hair has a large number of uses in areas ranging from agriculture to medicine to engineering industries. In addition, many new areas are being explored in scientific research. Large scale implementation of these uses, however, requires several environmental, social, and economic considerations.

Existing trade in human hair, which has evolved around some of these uses over centuries, provides several important lessons. The collection of hair can be based on many diverse systems driven by both economic and non-economic factors. Some of its products have sustained large markets in spite of competing products because of its better properties. This trade has provided livelihoods in many parts of the world but has also caused concerns about the ethical collection of hair, environmental and health safety at the hair processing industries, and product safety for consumers. Based on a systemic approach to the complete value addition chains from collection to consumption, most of these concerns can be addressed.

Using human hair by itself does not reduce the human hair accumulation in the waste streams because only certain (Type 1) uses that completely decay the hair during use reduce the hair "waste." In other applications, hair remains intact during use and then generates post-consumer waste. For some of these applications (Type 2), buy-back systems for collecting and recycling the hair are needed. For other (Type 3) uses in which the hair gets contaminated or blended with toxic or non-biodegradable materials, further research is needed to ensure safe recycling or decay of hair and the blended materials to return them back to nature.

There is a large scope for expanding utilization of human hair as its current percent utilization is very low. It has uses appropriate for entrepreneurs ranging from lay to highly technical personnel and for the variety of hair available in different locations. Due to its unique properties and ubiquitous availability, human hair can contribute significantly in many critical areas of public importance such as agriculture, medicine, construction materials, and pollution control.

A policy framework is outlined for expanding human hair utilization while ensuring social and environmental well-being. This includes development of legislations and standards as well as building support system for various uses according to their environmental impact, entrepreneurial needs, and market scope. The public must be made aware of its beneficial properties and safe practices of collection and use. With assistance of various stakeholders, it is possible to develop complete utilization systems for human hair, which will reduce solid waste and environmental problems, generate significant socioeconomic benefits for people, and reduce pressure on other nonrenewable materials and fossil fuels.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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