Pollution Impact Assessment and Water Footprint Calculation of Leather Industry in Bangladesh

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Certification of Thesis

We, the undersigned, certify that **Sumaya Humayra**, candidate for the degree of Master of Science in Chemical Engineering, has presented her thesis on the subject "**Pollution Impact Assessment and Water Footprint Calculation of Leather Industry in Bangladesh".** The thesis is acceptable in form and content. The student demonstrated a satisfactory knowledge of the field covered by this thesis in an oral examination held on October 11, 2020.

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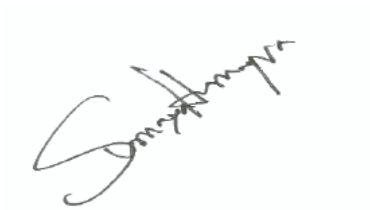

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Dedicated

to

My Beloved Family

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Abstract

Tanneries consume huge amount of water and chemicals each year and release effluents into the environment. Effluents produced from different stages of leather processing like the soaking, liming, chrome tanning, rechroming, neutralization, fatliqouring and dyeing processes can reduce surface water quality and damage human health. Pollutants generating from each stage of tanneries vary in concentration. So, proper study on characteristics of effluents from leather process can help to reduce water pollution. On the other hand, Water footprint can help to understand the water management of the leather sector in Bangladesh. Water footprint is actually an indicator of fresh water consumption in making a product in its life cycle. Water footprint data includes blue water footprint indicates surface or ground water, green water footprint indicates rain water and grey water indicates assimilation water of pollutants in effluents. The results from this study indicate that significant environmental impacts were caused during the leather production. Waste water samples have been collected from each stage of four tanneries for this study. The key pollution indicating parameters (pH, TDS, TSS, BOD and COD) have been analyzed for each sample. Those data have been used to calculate pollution load associated to different leather processing stages. It is found that almost 52% effluent generates from beam house and tan yard operations and 48% from post tanning operations. Almost 87% effluent generates from beam house in wet blue production. Effluent generates mostly from soaking (21%) and liming (34%) process of tannery. Maximum COD has been found in liming 142 kg/ton, then soaking 54 kg/ton and retanning 54 kg/ton. TSS has been high as well in tannery effluent such as in liming (121 kg/ton) and then neutralization (55 kg/ton). The control and reduction of soaking and liming effluents are the critical points to be considered to improve the environmental performance of the process. The Water footprint of bovine and ovine crust leather has been found to be 34000 m3/ton and 17300 m3/ton respectively. Water footprint assessment shows that grey water footprint of leather is almost 40-50%, blue water footprint of leather is almost 10-20% and green water footprint of leather 30-40% in total water footprint of leather from Bangladesh. Blue water footprint is higher in soaking, liming and finishing. Green water footprint does not belong in the processing stages of leather. Total green water footprint of leather mainly comes from green water footprint of feed crops of the farming animals. Grey water footprint is higher in soaking, liming, Fatliqouring and dyeing stages. So, by assessing water footprint and pollution load data, this study can help to understand the water footprint and pollution scenario of leather sector in Bangladesh.

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Abbreviation

BBS	Bangladesh Bureau of Statistics
BLRI	Bangladesh Livestock Research Institute
BOD	Biochemical Oxygen Demand
BTA	Bangladesh Tanners Association)
CETP	Central Effluent Treatment Plant
COD	Chemical Oxygen Demand
DLS	Department of Livestock Services
DO	Dissolved Oxygen
DoE	Department of Environment
EC	Electrical Conductivity
ECR	Environmental Conservation Rule
EPB	Export Promotion Bureau
EU	European Union
FAO	Food and Agriculture Organization
LCA	Life Cycle Assessment
LFMEAB	Leather goods and Footwear Manufacturers & Exporters Association of Bangladesh
TS	Total Solids
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
UBOD	Ultimate Biochemical Oxygen Demand
UNIDO	United Nations Industrial Development Organization

Chapter 1: Introduction

1.1. Background

Water consumption is increasing every year with the increase trade of leather and leather products, and so, the pollution load is rising as tanners are discharging waste water into water bodies with partial or no treatment. Tanneries in Bangladesh need proper management of water for better utility and efficient leather production. For this water footprint and pollution load data can help manufacturers, tanners and dealers to understand the environmental value of leather production. About 155 tanneries have been relocated to Savar beside Dhaleshwarie river for Government order, out of which 62 units have started production in new Savar tannery estate [1]. More tanneries are relocating and starting the production in new tannery location. As tanneries are highly water and chemical consuming industry, they release large amount of effluent everyday throughout the year. Previously The tanneries in Hazaribagh dumped 22,000 liters per day of toxic wastewater into the Buriganga [2]. Now after relocation, officials and tanners are concerned about the Dhaleshwarie river which can face same fate as Buriganga if proper measures are not taken to protect it [1].

Tannery waste water from beam house operations (stages include Soaking, Liming, Deliming, Pickling, Tanning) and post tanning operations (stages include Wet back, Rechroming, Neutralization, Retanning, Fatliqouring, Dyeing) contains pollutants like hair, flesh residue, blood, salts, sulphides, chrome complexes, ammonium salts etc. Characteristics and contaminants of wastewater from each stage differs from each other. Due to varieties in raw materials, processing, chemicals and water consumptions, pollution load generation during leather production varies a lot. Generally lower water consumption can lead higher pollutant concentration [3]. Untreated or partially treated tannery wastewater is discharged to the nearby water body, and highly hazardous to human health, aquatic lives and environment [4]. Waste water has been collected from each stage of four tanneries for this study. To understand water consumption, health and environmental hazard association to Bangladesh leather sector, it is important to analyze pollution load and water footprint associated to the sector. The water footprint is a scale of water measurement that looks at direct and indirect water use of a consumer or producer [5]. The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally. The blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product [6], The green water footprint refers to consumption of green water resources (rainwater stored in the soil as soil moisture) [7]. The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards [8]. The water footprint of leather thus offers a wider perspective on how tanners relate to the use of freshwater systems. It is a volumetric measure of water consumption and pollution. It is a measure of the severity of the local environmental impact of water consumption and pollution. The local environmental impact of a certain amount of water consumption and pollution depends on the vulnerability of the local water system and the number of water consumers and polluters that make use of the same system.

1.2 Objectives

The main objectives of the research are:

- Characterization of effluent produced from each stage of tanneries and assessment of the pollution impact of leather production with respect to assessment of the parameter like pH, BOD, COD, TDS and TSS.
- Water footprint calculation by calculating water footprint of feed crops, hides and skins, leather and leather products and to analyze the contribution of water footprint of leather sector in Bangladesh.

The outcomes of the research are:

i. Stage wise and product wise water footprint of Bangladesh leather sector;
ii. Pollution impact assessment of Bangladesh leather sector.

1.3. Scope and Methodology

There are two methods for calculation of water footprint, one of them is based on ISO-14040/44, 14067 standards and focuses on cradle to-gate approach and another is based on water footprint network approach in frame work of Hoekstra et al (2009) [9]. Both the methods use Life cycle assessment (LCA) of products. Life cycle assessment (LCA) is globally recognized as the leading method to measure product sustainability, as it can evaluate a wide range of metrics and provide a deeper understanding of 5 impacts, from cradle to grave. For this thesis, the LCA approach is based on water footprint network approach in frame work of Hoekstra et al (2009) [5]. Each of these steps is described as follows:

1.3.1. Defining Goals and Scope

The functional unit and system boundary of the finished leathers will be defined. Therefore, all the inputs and outputs will be calculated in relation to the production of corresponding functional unit of finished leathers. The illustration of the brief system boundary is given below in figure 1.

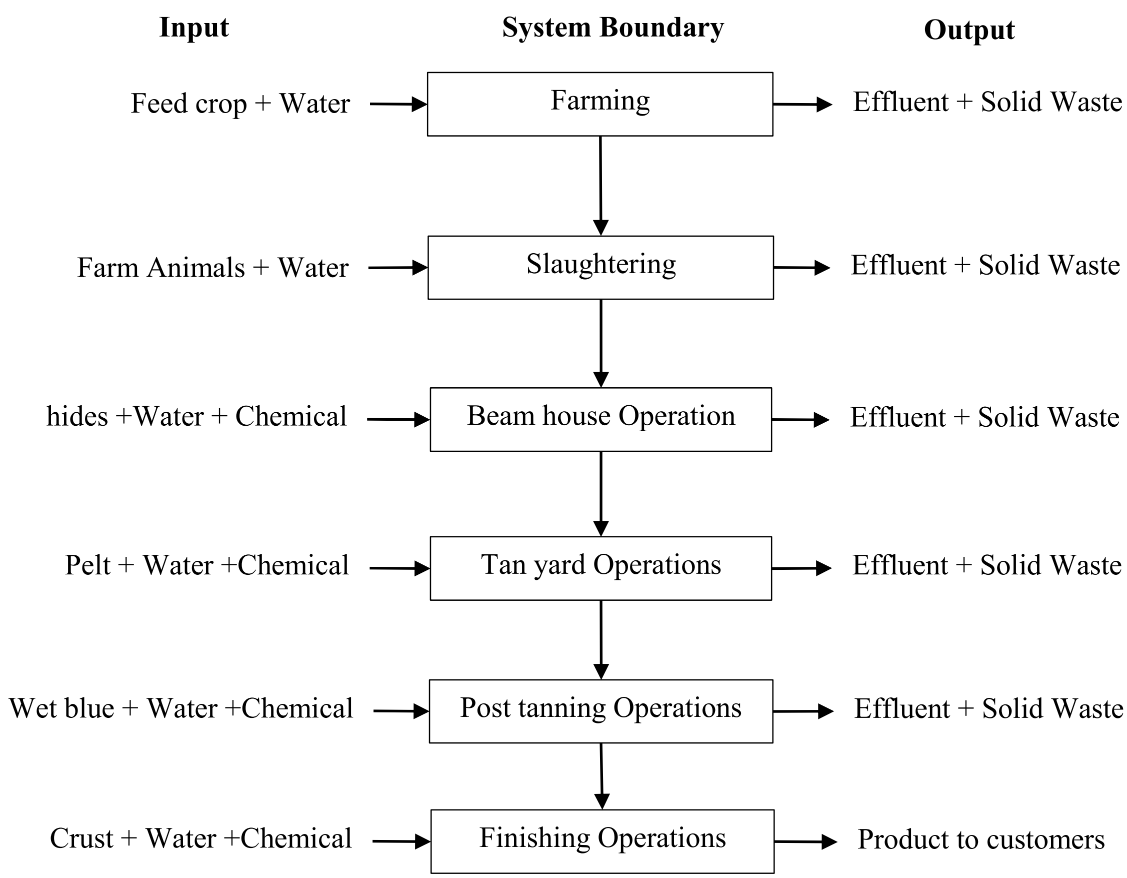


Figure 1: Process flow chart of leather production

1.3.2. Water Footprint Calculation

The green and blue water footprint associated to the leather sector will be calculated by introducing 'Grazing Model' where evapotranspiration data will be used with grazing data of beef cattle, buffaloes, goat and sheep in Bangladesh. Evapotranspiration can be estimated by the model that uses data on climate, soil properties and crop characteristics as input. the CROPWAT model will be used in this research which is developed by the Food and Agriculture Organization (FAO) of the United Nations [10] [11]. CROPWAT model will produce evapotranspiration data which will be used with production and production area data. This method will be used for the feed crop rice straw, rice bran, wheat bran etc. Evapotranspiration data will be used differently in case of grass. The grey water footprint will also take Fertilizer application rates, leaching fraction, ambient water quality standards, natural concentrations data as its input. Water consumption, livestock population, production system, slaughter rate data will be used to calculate the blue and grey water footprint of cattle, buffaloes, goats and sheep. Hides and skins of the livestock will be gathered in the slaughterhouse which is preserved and taken to the production. In this research water footprint of tanneries, where skins and hides are being processed, will be calculated by the chain summation approach. In this approach, the water footprints that are associated with the various process steps in the production system will be calculated.

1.3.3. Water Footprint Sustainability Assessment (Environmental Perspective)

Environmental water footprint sustainability can be considered at three distinct levels. Local water footprint impacts may occur due to overexploitation or pollution of surface or groundwater bodies. For this research the factors that are considered are:

- Water footprint of raw material (hides and skins of livestock animal)
- Water footprint contribution percentage in leather production
- Water consumption for leather production
- Water pollution level in tanneries

Environmental impacts at the river basin level may occur when many small abstractions or waste flows add up and cause downstream impacts on aquatic ecosystems or terrestrial ecosystems adjacent to the river.

1.3.4. Water Footprint Response Formulation

It is often thought that water footprint reduction is only relevant in locations where problems of water scarcity and pollution exist. One can pose the rhetoric question why to reduce the water footprint in an area where water is abundantly available. Or why to reduce the green water footprint in agriculture if the rain comes anyhow and will otherwise remain unproductive? The rationale behind these questions is: when locally the water level can get depleted, the water use must be sustainable.

1.3.5. Pollution Impact Assessment

Key pollution indicating parameters such as: Biolo
gical Oxygen demands (BOD), Chemical Oxygen Demands (COD), Total Dissolved Solids (TDS), Total Suspended Solids (TSS) of effluents can be determined for characterization of wastewater of tanneries. It can help to understand the impacts of effluents on the ecosystem and biodiversity of river.

1.4. Organization of Thesis

The thesis report contains total six chapters. The organization of the chapters of the thesis report is mentioned and descried below:

Chapter 1 contains introduction of the report and also has background, objectives, goals and scope of the thesis.

Chapter 2 provides literature review on leather and leather products along with the leather processing, Pollutants generation in tanneries, National effluent quality standard and international legislation for tannery effluent and Concept of water footprint discussion.

Chapter 3 presents the methodology followed in this study, including selection of sampling stages of leather processing and major point sources, in-situ water quality data collection and water sampling procedure, laboratory analysis of water samples collected from tanneries, and calculation and assessment of the water footprint and pollution load.

Chapter 4 presents the characteristics of waste water from tanneries based on water quality data generated in this study. It also presents the estimated pollution load from major stages of tanneries leather processing, based on the measurement carried out in this study. Also, it presents the grey, blue and green water footprint of pelt, wet blue and crust leather of Bangladesh.

Chapter 5 presents the assessment of water footprint (Grey, Blue, Green) for leather production and also gives pollution impact assessment by analyzing parameters like pH, BOD, COD, TDS and TSS.

Chapter 6. presents the major conclusions from this study and the suggestions for the betterment of water management in tanneries of Bangladesh and future research works in this area.

Chapter 2: Literature Review

This chapter will explain briefly about the process of leather production and the concept of water footprint. And this chapter will also contain the description of important parameters to calculate the pollution load of a certain section. There are several approaches for explaining the water footprint for a product. For this research, the product has been specified to be leather products. That is why this chapter will give the perspective for the entire concept of water footprint of leather products.

2.1. Leather and Leather Products in Bangladesh

Leather and footwear industry considered to be the second largest sector after Readymade Garments (RMG) in terms of export products from Bangladesh. But leather sector in Bangladesh has been through some important events recently like relocation of tanneries and newly formed Savar tannery estate, Downward trend in export of leather products but high growth in footwear export, many obstacles in running Central Effluent Treatment Plant (CETP) in Savar etc. which are discussed below:

2.1.1. Recent Export Downward Trend Analysis of Bangladesh Leather Sector

Bangladesh exported total USD 866.45 million from leather export in Fiscal year (FY) 2013. Among them USD 305.02 million is from exporting footwear, USD 161.62 million is from exporting Leather products & USD 400 million is from exporting Raw Leather. In the FY15, earnings from leather footwear, leather products & leather were USD 483.81 million, USD 249.16 million, and USD 397.54 million respectively (See figure 02) [12] [13]. In FY 2020 the leather sector earns less than 1 billion (See figure 03) which is given the reason of environmental issues.

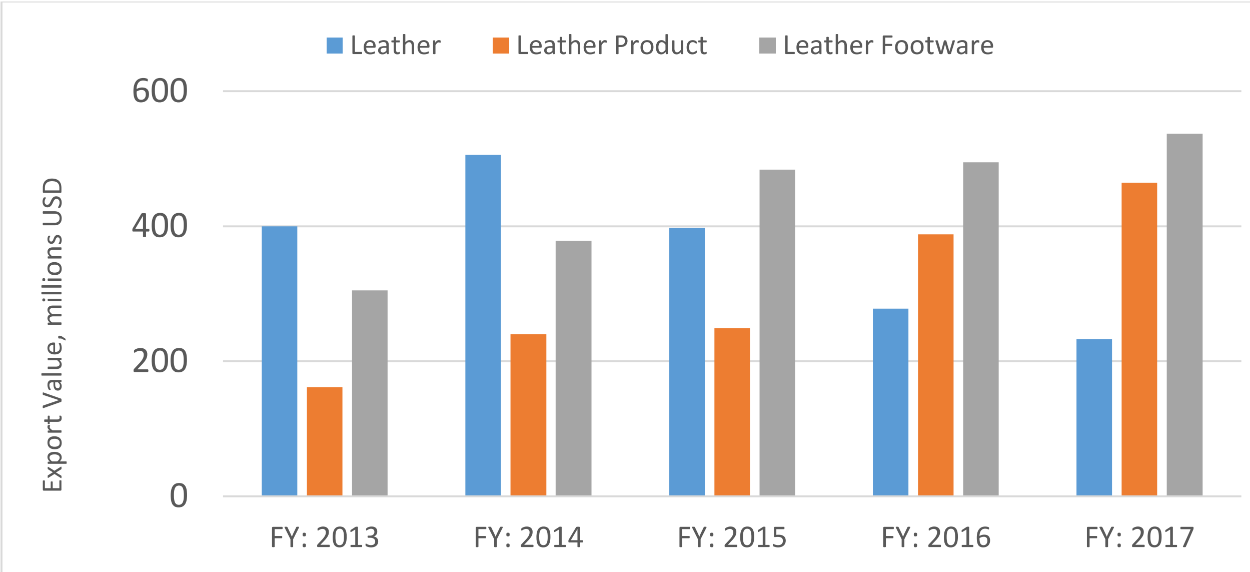


Figure 2: Export value of leather sector in Bangladesh *[12]*

But recent study shows a fall of export earnings in leather sector which is 6.06% all to $1.01 billion in the just concluded fiscal year 2019, as non-compliance in environmental issues holds back foreign buyers [14]. In the FY18, the export earnings from the leather sector were $1.08 billion and the sector saw 12% decline in export earnings (See figure 03). Of the total earnings from leather sector in FY19, leather products earned $247.28 million, down by 26.58% [15].

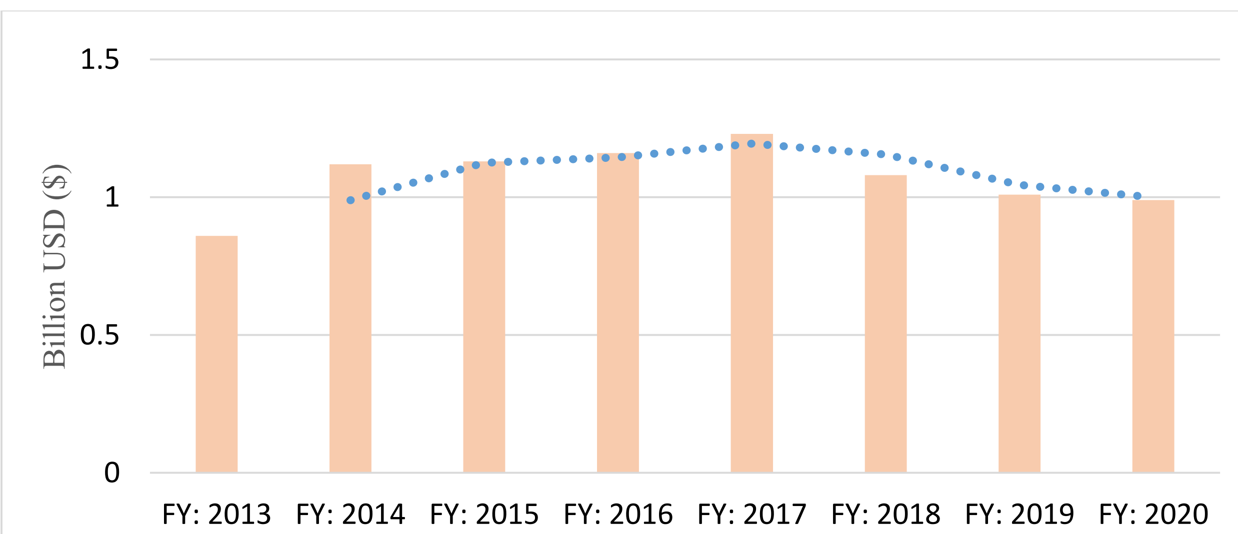


Figure 3: Export trend of leather sector in Bangladesh [12]

Bangladesh exports raw leather mainly to China and Germany. And other major countries for leather exports are Japan, Germany, Hong Kong, USA, Spain, Italy, Korea Republic and Netherland (See table 1).

Table 1: Major importing countries of Bangladesh leather and leather products & footwear *[16]*

Country	FY: 2013	FY: 2014	FY: 2015
Germany	72.44	103.53	142.89
China	41.92	172.65	165.60
Japan	123.08	133.27	117.40
USA	33.49	57.59	98.52
Spain	41.96	51.96	60.01
Italy	37.75	38.17	44.40
France	22.88	21.19	25.05
UK	5.98	9.34	15.70
UAE	2.60	3.24	17.51

*Value in million US$

2.1.2. Growth in Leather Footwear Industries:

For many reasons there is a decline in leather and leather goods export earnings trend but the growth in leather footwear section is also noticeable. Leather Footwear Industries are exporting revenue is potentially high. The footwear industry recorded 27% growth in four years, from FY: 2012 to FY: 2015 (See figure 04). Bangladesh's footwear industry shares 3% of the global leather market in volume while 95% of its output is exported. Apex Footwear, Jennys Shoes, Bay Footwear, Leatherex and Bata Shoe are leading exporters of footwear. Companies like Orion, Crescent and others have also joined the industry with young and industrious workforce. The LFMEAB report said Japan and Germany are now the biggest markets for Bangladeshi footwear which is also exported to Italy, the UK, France, Belgium, the USA, Sweden, Spain, Saudi Arabia, Taiwan, Hong Kong, Canada and Korea [16].

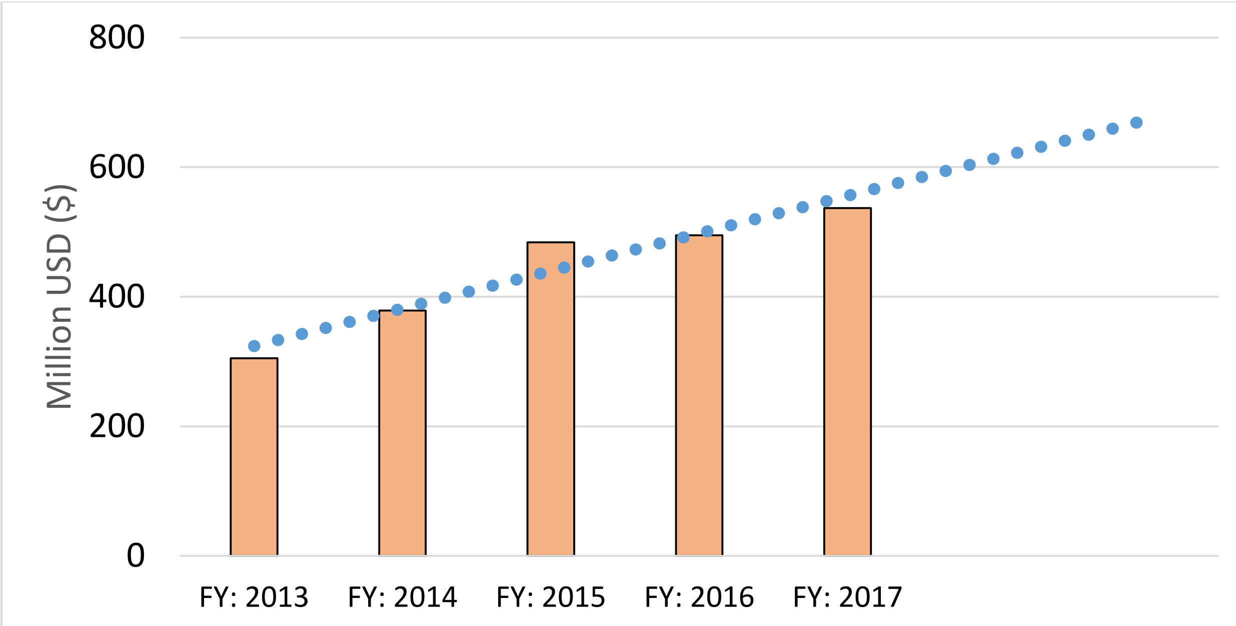


Figure 4: Leather footwear export growth of Bangladesh *[12]*

2.1.3. The Relocation and Savar Tannery Estate:

Relocation of all tanneries from Hazaribagh implemented by BSCIC to a properly designed and controlled new industrial estate in Savar is practically the only feasible solution offering safe, yet economic conditions for maintaining this important business, keep several dozen thousands of labor employed and earning much needed (for the national economy) export revenue [17]. Savar tannery estate is brand new epicenter for leather production. In total, 155 factories have been shifted to Savar. Of these, 125 factories are running and 25 tanneries have fully started operations but are processing only crust leather [18].

2.1.4. The Infrastructure of Central Effluent Treatment Plant (CETP):

To prevent the dangerous pollution that occurred at the old Dhaka site and bring the industry into better compliance with customer environmental requirements, the new location includes a central effluent treatment plant (CETP), able to treat 30,000m^3 of liquid effluents a day, and additional facilities for chrome recovery, water treatment, and sludge treatment. But some planned capabilities are not yet installed, and the CETP is not yet running at full efficiency, with the result that sludge are now dumped in an open yard, and untreated water is regularly dumped into the neighboring Dhaleshwari river, causing severe pollution [19].

2.1.5. Livestock Scenario in Bangladesh

The farm animals in Bangladesh mostly include cattle, buffalo, goat and sheep. Most of the farm animals are still reared under traditional production system except some commercial dairy and beef fattening farms have developed [20] [21]. Landless and small farmers hold about 62.6% of the total large ruminants and used as sources of income and nutrition, and considered as a resource for employment and poverty alleviation [22]. Beef fattening, dairying and heifer rearing are the production systems for exploration of cattle germplasm in the country. About 6.0 million cattle slaughtered annually and used as sources of beef and leather [23]. The goat population of Bangladesh is 25.766 million [23]. About 52.4% of the total goats are kept by landless and small farmers and the rest 47.67% is kept by the medium and large farmers [21]. A total of 3.335 million sheep are available in the country [23]. Small and landless farmers rear about 37.5%, medium farmers 40.0% and large farmers 22.3% [21]. Sheep in Bangladesh are mostly indigenous type and is called Bangla sheep.

Table 2: Livestock population of Bangladesh *[23]*

Species	FY: 2013	FY: 2014	FY: 2015	FY: 2016	FY: 2017	FY: 2018
Cattle	233.41	234.88	236.36	237.85	239.35	240.86
Buffalo	14.50	14.57	14.64	14.71	14.78	14.85
Sheep	31.43	32.06	32.70	33.35	34.01	34.68
Goat	252.77	254.39	256.02	257.66	259.31	261.00
Total Ruminant	532.11	535.90	539.72	543.57	547.45	551.39
Total Livestock	3494.75	3577.62	3662.65	3749.90	3839.45	3931.3

Values in lakh number

Bangladesh has potential to produce approximately 31 million pieces of hides and skins and then leather. Table 3 shows the data of annual production capacity of hides skins estimation in which Bovine hides are 9 million, sheepskins 16 million and goat skins 6.14 million [24] [25].

Table 3: Estimated annual production capacity of raw materials *[24] [25]*

Item	Capacity (million pieces)
Bovine hides and skins	9
Sheepskins and lambskins	16
Light Leather from sheep and goat	6.14

2.1.6. General Classification of Leather Articles:

Leather exports primarily in three categories. Leather, leather Goods and footwear. Raw leather is exported as finished leather, crust leather and wet blue leather. Leather goods are included garments, shoes, belts, bags, jackets, suitcase, wallets and others. LFMEAB shows the data in table 4 that annual production has been estimated of footwear 364.5 million pair, belt 1700 pieces, bags 80 million and other leather products 3100 million pieces [26].

Table 4. Estimated annual production of leather products *[16]*

Item	Capacity (million pieces)
Footwear	364.50 (pairs)
Belts	1700
Bags	80.22
Small Leather Goods	3100

The Biggest leather consumption sector is footwear (almost 51%). After that leather is used in many products like clothing (25%), furniture upholstery (5%), handbags and luggage (8%), wall painting, gloves (7%), hats, coats, dress, wallets etc. (See figure 05).

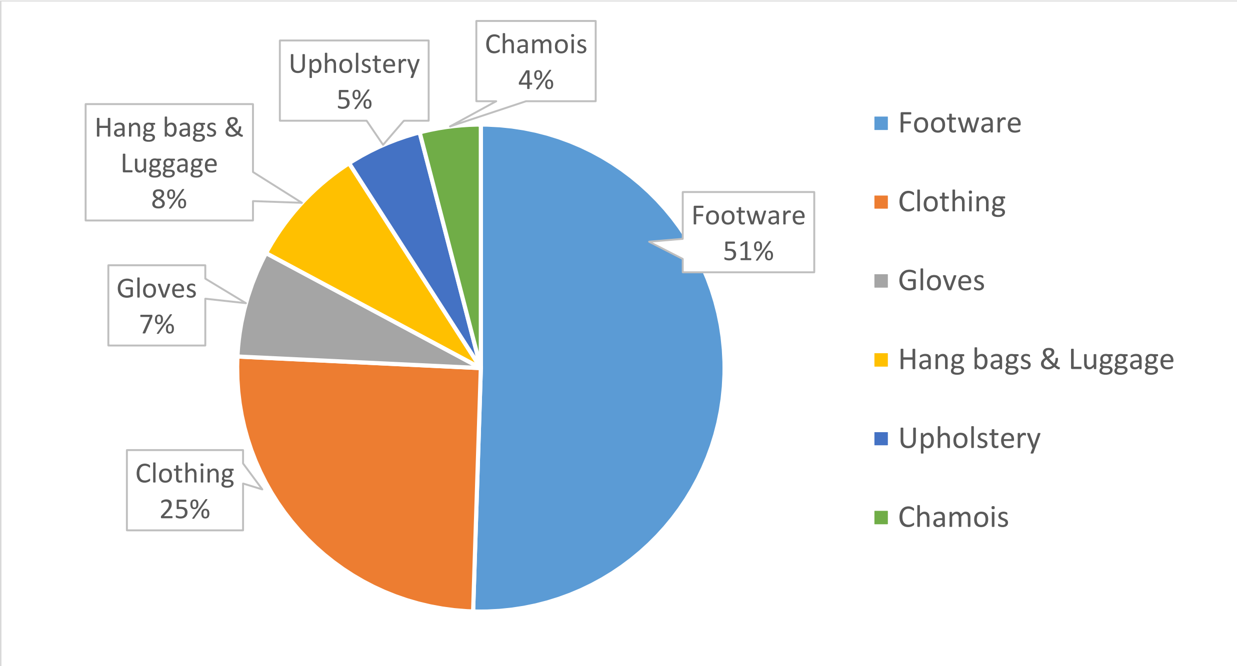


Figure 5: Estimation of leather used in products *[16]*

Various types of leather are produced by the choice of raw material and by the variation of a sequence of tanning processes. In general, leather is sold in many forms which has been described below:

2.1.6.1. Full Grain Leather or Top Grain Leather

Full grain leather or top grain is referring to the upper section of a hide that contains the epidermis or skin layer. It refers to hides that have not been sanded, buffed or snuffed (otherwise known as corrected) in order to remove imperfections on the surface of the hide. Only the hair has been removed from the epidermis. The grain remains in its natural state which will allow the best fiber strength, resulting in greater durability. The natural grain also has natural breathability, resulting in greater comfort for clothing.

The natural full grain surface will wear better than other leather. Rather than wearing out, it will develop a natural "Patina" and grow more beautiful over time. The finest leather furniture and footwear are made from full grain leather. For these reasons only the best raw hides are used in order to create full grain or top grain leather. Full grain leathers can mainly be bought as two finish types: aniline and semi-aniline [27].

2.1.6.2. Corrected Grain Leather

Corrected grain leather is any top grain leather that has had its surfaces sanded, buffed or snuffed in order to remove any imperfection on the surface due to insect bites, healed scars or brands. Top grain leather is often wrongly referred as corrected grain. Although corrected grain leather is made from top grain as soon as the surface is corrected in any way the leather is no longer referred as top grain leather. The hides used to create corrected leather are hides of inferior quality that do not meet the high standards for use in creating aniline or semi-aniline leather. The imperfections are corrected and an artificial grain applied. Most Corrected leather is used to make Pigmented leather as the solid pigment helps hide the corrections or imperfections. Corrected grain leathers can mainly be bought as two finish types: semi-aniline and pigmented [28].

2.1.6.3. Split Leather

Split leather is leather that is created from the fibrous part of the hide left once the top grain of the raw hide has been separated from the hide. During the splitting operation the grain and drop split are separated. The drop split can be further split (thickness allowing) into a middle split and a flesh split. In very thick hides the middle split can be separated into multiple layers until the thickness prevents further splitting. Split leather then has an artificial layer applied to the surface of the split and is embossed with a leather grain. Splits can be also used to create Suede [28].

2.1.6.4. Suede Leather

Suede leather is "fuzzy" on both sides. The strongest suedes are usually made from grain splits (that have the grain completely removed) or from the flesh split that has been shaved to the correct thickness. Suede is less durable than top grain. Suede is cheaper because many pieces of suede can be split from a single thickness of hide, whereas only one piece of top grain can be made. However, manufacturers use a variety of techniques to make suede appear to be full-grain. For example, in one operation, glue is mixed with one side of the suede, which is then pressed through rollers; these flatten and even out one side of the material, giving it the smooth appearance of full grain [28].

2.1.6.5. Latigo

Latigo is one of the trade names for this product. A reversed suede is a grained leather that has been designed into the leather article with the grain facing away from the visible surface. It is not a true form of suede. There are two other descriptions of leather commonly used in specialty products, such as briefcases, wallets, and luggage [29].

2.1.6.6. Nappa Leather

Napa leather is chrome-tanned and is extremely soft and supple and is commonly found in higher quality wallets, toiletry kits, and other personal leather goods [30].

2.2. Description of leather processing

For decades the most credited tanning theory explained the stabilization of the collagen with the formation of cross-links within its triple helix structure [31]. It actually seems that a modification of the supramolecular water sheath also plays a key role in this transformation [32]. All tannages result in an increase of the hydrothermal stability of the collagen, the extent of which depends mostly on the chemical nature of the tanning agent. Leather process can be different on basis of raw materials and products requirement (See figure 06 and 07)

2.2.1. Curing

Raw hides and skins must be preserved to stop them deteriorating before the leather-making process can begin. Methods of preservation include salting, chilling, freezing and the use of biocides. The most common preservation systems act by reducing the bacterial activity by means of drying, salting or refrigerating the substrate as soon as possible since flaying. Among these methods, salting techniques are the most viable and, therefore, industrially widespread, although a high load of chloride ion is inevitably released into the waste water [33] [34] [35].

2.2.2. Soaking

Cured hides or skins are soaked in water for several hours to several days. This allows them to reabsorb any water they may have lost in the curing process or during transportation. It also helps to clean them of salt and dirt. In some Countries the solid fraction of the salt used for conservation is removed by mechanical or manual treatment prior to the addition of water, in order to reduce the concentrations of chlorides in the wastewater [36]. Salt can be recovered for other uses after appropriate purification [37].

2.2.3. Liming

Liming removes the epidermis and hair. This also results in alkaline swelling of the pelt to cause a controlled breaking of some of the chemical crosslinks of the collagen. In this phase most of the unwanted substances (non-structured proteins, fats, hyaluronic acid, etc.) are removed and the properties of the skin protein are altered [38].

2.2.4. Fleshing

After liming the pelt is passed through a machine to remove fleshy tissue from the flesh side. Hides may be split into layers at this stage or after tanning.

2.2.5. Deliming

The principal action of deliming is to gradually neutralize the alkali in the pelt, avoiding rapid changes in pH which could lead to distortion or disruption of the tissues. The aim of the deliming stage is to solubilize residual lime and deflate the structure by lowering the pH down to 8.5-9.0, ideal for the enzymatic digestion that will occur during the next bating step [39].

2.2.6. Bating

A long delime can significantly improve the removal of any remaining lime, scud (miscellaneous debris) and residual components broken down during liming. Bating - based on the use of enzymes - completes this process so that the pelt is flat, relaxed, clean and ready for pickling and tanning.

2.2.7. Pickling and Degreasing

Weak acid and salt solutions are used to bring the pelt to the weakly acid state required for most tanning processes. Stronger pickling solutions are used to preserve pelts so that they can be stored or transported in a stable form over periods of several months. The pickling stage prepares the skins for the subsequent tanning by treatment with acids (formic and sulphuric acid are the most used). Since pH is driven well below the isoelectric point, sodium chloride is added to prevent a dangerous acid swelling of the pelt [40] [41]. Solvents or water-based systems can be used to remove excess grease before tanning.

2.2.8. Tanning

Tanning converts the protein of the raw hide or skin into a stable material, which will not putrefy and is suitable for a wide variety of purposes. Tanning materials form crosslinks in the collagen structure and stabilize it against the effects of acids, alkalis, heat, water and the action of micro-organisms. For decades the most credited tanning theory explained the stabilization of the collagen with the formation of cross-links within its triple helix structure [31]. It actually seems that a modification of the supramolecular water sheath also plays a key role in this transformation [32].

2.2.9. Splitting

A splitting machine slices thicker leather into two layers. The layer without a grain surface can be turned into suede or have an artificial grain surface applied. Bovine wet blue under goes this mechanical process but ovine leather is not thick enough for this.

2.2.10. Shaving

A uniform thickness is achieved by shaving the leather on the non-grain side using a machine with a helical blade mounted on a rotating cylinder. Wet blue leather has been usually taken to store after the shaving process.

2.2.11. Neutralization

Neutralizing removes residual chemicals and prepares the leather for further processing and finishing. Additional tanning material may be applied to give particular properties which are required in the finished leather.

2.2.12. Dyeing

The dyeing of leather into a wide variety of colors plays an important part in meeting fashion requirements. Some leathers are only surface dyed, while others need completely penetrated dyeings, as is the case with suede leathers.

2.2.13. Fatliquoring

Fatliquoring introduces oils to lubricate the fibers and keep the leather flexible and soft. Without these oils the leather will become hard and inflexible as it dries out.

2.2.14. Samming

This process reduces water content to about 55% and can be achieved by a number of machines, the commonest being like a large mangle with felt covered rollers.

2.2.15. Setting out

Setting is mechanical process in which the leather is stretched out and the grain side is smoothed. This process also reduces the water content to about 40%.

2.2.16. Final drying

Leather is normally dried to 10-20% water content. This can be achieved in a number of ways and each method has a different effect on the finished leather:

2.2.17. Staking and dry drumming

A staking machine makes the leather softer and more flexible by massaging it to separate the fibers. To finish off the leather may be softened by the tumbling action inside a rotating drum.

2.2.18. Buffing and Brushing

The flesh surface is removed by mechanical abrasion to produce a suede effect or to reduce the thickness. In some cases, the grain surface is buffed to produce a very fine nap, e.g. nubuck leathers. After buffing the leather is brushed to remove excess dust.

2.2.17. Finishing

The aims of finishing are to level the color, cover grain defects, control the gloss and provide a protective surface with good resistance to water, chemical attack and abrasion. These are three different types of leather finishes which are commonly used by leather finishers. They are:

Water Type finishes: This may be based on pigment, protection binders, such as casein, shellac, gelatin, egg, and blood albumin, waxes and mucilaginous substances like decoration of linseed. These finishes are mainly used for glazed finishers, which are required to be glazed by glazing machine. The binders in the finish are intended to hold the pigments or dyes in suspension and bound firmly on the leather surface. Softness, glazing properties and 'handle' are contributed by water soluble plasticizers, waxes and mucilaginous matters. Recently water type finishes based on pigment or dyes and resin dispersion are increasingly used to achieve especial effect on the finished leather. The use such finishes produced may improvement over the conventional protein based finishes such as better adhesion and flexibility of the finish, improved filling and sealing properties and greater uniformity of the flesh.

Solvent Type Finishes: In contrast to eater type finishes solvent-based finishes contain as a binder polyurethane or collodion (Nitro-cellulose). These finishes are dissolved in organic solvents such as butyl acetate, cyclohexanone, etc. These finishes are widely used for finishing based on vinyl resin instate of nitro cellulose have shown improved resistance to flexing and better flexibility at low temperature. They have been successful used on upholstery leather, case leather, case leather and certain military where low temperature flexibility is necessary.

Emulsion Type Finishes: Emulsion type finishes consist of nitrocellulose or resins. Such emulsions are being widely used to confer to confer combining properties of water and lacquer finish. Lacquer emulsion top coast for upper, garment and glove leather are gaining wide acceptance.

For more classification of leather finishes:

a. According to the finishing materials:

1) Casein Finish
2) Resin binder or polymer finish
3) Nitro-cellulose finish
4) Polyurethane finish

b. According to the finishing technique:

1) Glazed finish

2) Glazed/ plate finish
3) Plate finish
4) Embossed finish
5) Spray finish
6) Curtain coating finish

c. According to the finishing effect:

1) Aniline finish
2) Semi-aniline finish
3) Opaque finish
4) Easy care finish
5) Antique finish
6) Fancy finish
7) Two-tone finish

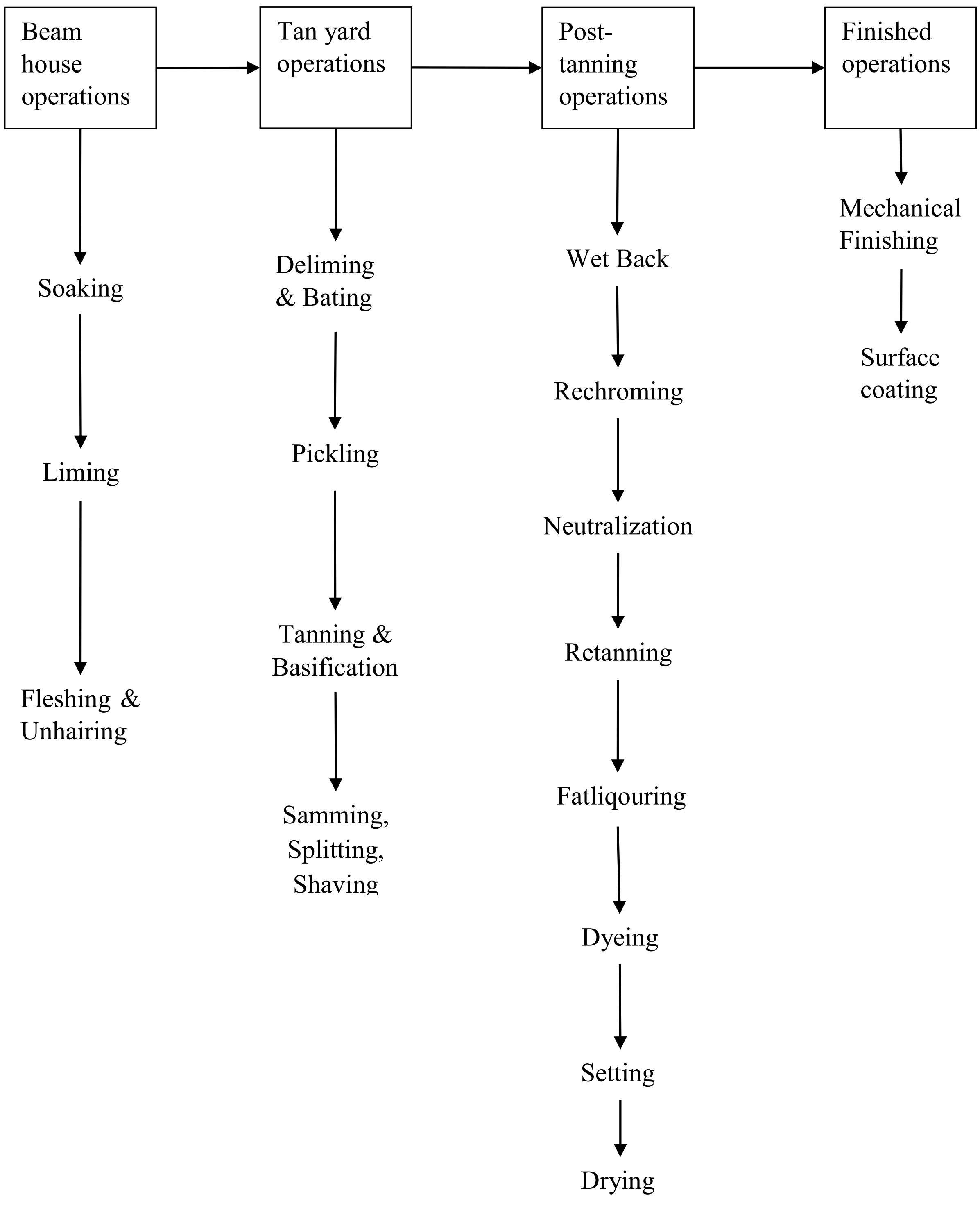


Figure 6: Overall view of leather processing (bovine leather)

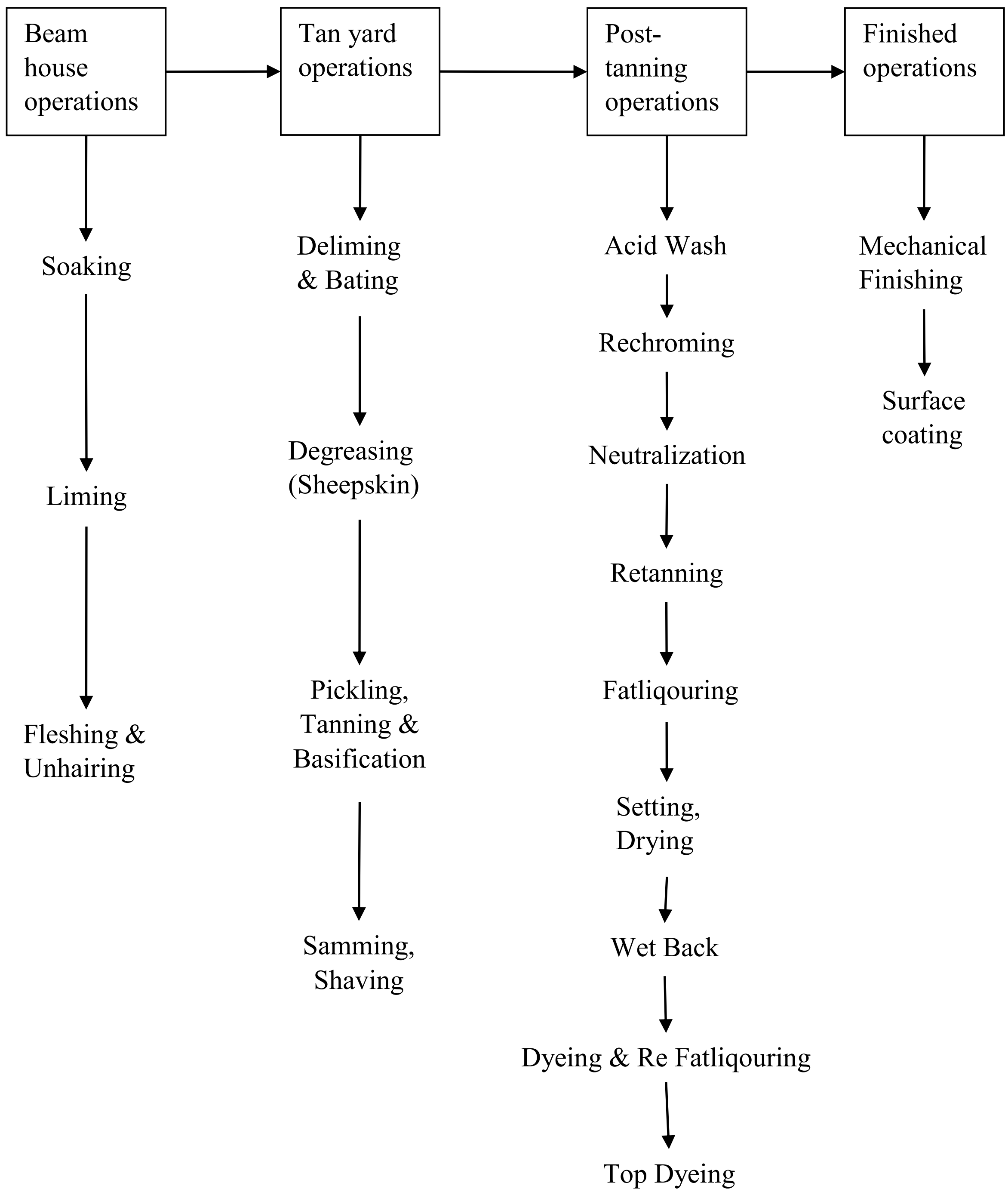


Figure 7: Overall view of leather processing (ovine leather: goatskin or sheepskin)

2.3. Pollutants Generation in Tanneries

2.3.1. Solids

The solids to be found in tannery effluent fall into several distinct categories. They are mainly Suspended solid, Settleable solids, Gross solids which are described below:

2.3.1.1. Suspended Solids (SS)

The suspended solids component of an effluent is defined as the quantity of insoluble matter contained in the wastewater. These insoluble materials cause a variety of problems when discharged from a site; essentially, they are made up of solids with two different characteristics.

a. Solids with a Rapid Settling Rate (Settleable Solids)

Settleable solids comprise material that can be seen in suspension when an effluent sample is shaken, but settles when the sample is left to stand. The majority of these solids settle within 5 to 10 minutes, although some fine solids require more than an hour to settle. These solids originate from all stages of leather making; they comprise fine leather particles, residues from various chemical discharges and reagents from different waste liquors.

Large volumes are generated during beamhouse processes. If the waste waters are to be treated in sewage works or undergo traditional effluent treatment, the main problems that arise are due to the large volume of sludge that forms as the solids settle. Sludge often contains up to 97% water, giving rise to huge quantities of 'light' sludge. Even viscous sludge has a water content of around 93%, and can easily block sumps, sludge pumps and pipes. All this sludge has to be removed, transported, dewatered, dried and deposited, thus placing an inordinate strain on plant, equipment and resources [42]. If the waste water is to be discharged into surface water, the rate of flow will determine the distance the material is carried before settling on the stream or river bed. Even a thin layer of settled sludge can form a blanket that deprives sections of the river or lake bed of oxygen. Plant and aquatic life die and decomposition sets in.

b. Semi-Colloidal Solids

Semi-colloidal solids are very fine solids that, for all practical purposes, will not settle out from an effluent sample, even after being left to stand for a considerable period of time. They can, however, be filtered from solutions. Together with the more readily settleable solids, they thus comprise the suspended solids of an effluent that can be measured analytically. Most of these solids are protein residues from the beamhouse operations - mainly liming processes; however, large quantities are also produced owing to poor uptake in vegetable tanning processes, another source being poor uptake during retanning. Semi-colloidal solids will not directly cause a sludge problem. They can be broken down over an extended period by bacterial digestion and they produce solids, which will eventually settle (see section 2 below). Suspended solids analysis measures both components and the technique are simple. A known volume of effluent is taken and filtered through a filter paper which is then dried and reweighed. The difference between this weight and that of the original paper is the weight of the dry solid material contained in the sample [42].

2.3.1.2. Settleable Solids

Although suspended solids analysis is the method most commonly used to assess insoluble matter, analysis of the settleable solids content is sometimes required. The settleable solids content is determined by leaving the shaken sample to settle and then filtering a known volume of the semi-colloidal matter remaining in suspension. After drying and weighing, the quantity of semi-colloidal matter can be calculated. The difference between the suspended solids and this figure is the settleable solids content.

2.3.1.3. Gross Solids

Gross solids are larger than a sampling machine can handle, hence they are not measured. Their presence, however, is clear to see and the dangers they pose are fully recognized. The waste components that give rise to this problem are often large pieces of leather cuttings, trimmings and gross shavings, fleshing residues, solid hair debris and remnants of paper bags. They can be easily removed by means of coarse bar screens set in the waste water flow. If, however, they emerge from the factory, they settle out very rapidly. Major problems can develop, if these materials settle in the pipe work as they lead to blockages. The problems can be very serious when blockages occur in inaccessible pipework. The cost of replacing a burned out motor or broken rotors is high. If discharged into gullies, ditches or water courses, the debris rapidly accumulates causing blockages and leading to stagnation.

2.3.2. Oxygen Demand

Many components in effluents are broken down by bacterial action into more simple components. Oxygen is required for both the survival of these bacteria (aerobic bacteria) and the breakdown of the components. Depending on their composition, this breakdown can be quite rapid or may take a very long time. If effluent with a high oxygen demand is discharged directly into surface water, the sensitive balance maintained in the water becomes overloaded. Oxygen is stripped from the water causing oxygen dependent plants, bacteria, fish as well as the river or stream itself to die. The outcome is an environment populated by non-oxygen dependent (anaerobic) bacteria leading to toxic water conditions.

A healthy river can tolerate substances with low levels of oxygen demand. The load created by tanneries, however, is often excessive, and the effluent requires treatment prior to discharge. This is often achieved by using bacteria in a properly operated effluent treatment plant: a process demanding high levels of oxygen. Oxygen induction can be achieved by blowing large volumes of air into the effluent: a process entailing a high-energy demand and, as a corollary, high capital and operational costs. Under normal working conditions, both water and carbon dioxide are produced in large volumes; the process, however, depends upon bacterial growth. As the bacteria die, they form sludge that has to be treated and ultimately disposed of. This sludge has high water content and is often quite difficult to dewater, thus adding considerably to the treatment costs. In order to assess an effluent's impact on discharge to surface waters or determine the costs of treatment, the oxygen demand needs to be determined. This can be achieved in two different ways:

2.3.2.1. Biochemical Oxygen Demand (BOD_5)

The technique for measuring biochemical oxygen demand (BOD) is complex. Essentially, the effluent sample once shaken is left to stand for one hour so that all settleable solids are excluded from the analysis. The liquor above the precipitate (supernatant) is drawn off and used in the analysis. A suitable volume of this sample is diluted in water, pH adjusted, and seeded with bacteria (often settled sewage effluent). The samples are then incubated in the dark for five days at 20 " 1ºC. The oxygen dissolved in the water is used by the bacteria while over time the organic matter in the sample is broken down. The oxygen remaining is determined either by means of an oxygen meter or by analysis. The level of oxygen demanded by the effluent can be calculated by comparison to the blank effluent-free samples.

The BOD_5 analysis, generally termed BOD, is widely used to assess the environmental demands of waste water. This method of detection has various weaknesses: the bacterial cultures can vary and the analysis is a highly sensitive process. If the most stringent care is not taken during the preparation and the analysis itself, the results can be misleading. It should also be remembered that although BOD is a measure of the oxygen requirements of bacteria under controlled conditions, many effluent components take longer than the period of analysis to break down. Some chemicals will only be partially broken down, while others may not be significantly affected. Typically, vegetable tanning wastes have a long breakdown period, often quoted as being up to 20 days. These longer digestion periods can apply to a variety of the chemicals used in manufacturing leathers, including certain retanning agents, some synthetic fatliquors, dyes and residual proteins from hair solubilization. This longer breakdown period means that the environmental impact is spread over a larger area as the waste water components are carried greater distances before breaking down [43] [44].

2.3.2.2. Chemical Oxygen Demand (COD)

This method measures the oxygen required to oxidize the effluent sample wholly. It sets a value for the materials that would normally be digested in the BOD5 analysis, the longer term biodegradable products, as well as the chemicals that remain unaffected by bacterial activity. The method is very aggressive. A suitable volume of effluent is boiled with a powerful oxidizing agent (potassium dichromate) and sulphuric acid. As the effluent components oxidize, they use oxygen from the potassium dichromate, the amount used to be determined by titration. This method is often favored as it provides rapid results (hours as opposed to days). It is more reliable and cost effective as it is easier to manage larger numbers of samples. The results are always higher than those obtained using the BOD5 analysis. As a rule of thumb, the ratio between COD: BOD is 2.5:1, although in untreated effluent samples variations can be found as great as 2:1 and 3:1. This depends on the chemicals used in the different leather making processes and their rate of biodegradability. It should be noted that both techniques are based on settled effluent, not filtered. The semi colloidal material that forms part of the suspended solids is also included in the BOD and COD determinations. Normally 1 mg/l suspended solids will generate a COD increase of approximately 1.5 mg/l [45] [44].

2.3.3. pH value

Acceptable limits for the discharge of waste waters to both surface waters and sewers vary, ranging between from pH 5.5 to 10.0 [46] [47]. Although stricter limits are often set, greater tolerance is shown towards higher pH since carbon dioxide from the atmosphere or from biological processes in healthy surface water systems tends to lower pH levels very effectively to neutral conditions. If the surface water pH shifts too far either way from the pH range of 6.5 - 7.5, sensitive fish and plant life are susceptible to loss. Hence, the beamhouse wastewater is characterized by an alkaline pH and tanning wastewater by a very acidic pH [48]. Municipal and common treatment plants prefer discharges to be more alkaline as it reduces the corrosive effect on concrete. Metals tend to remain insoluble and more inert, and hydrogen sulphide evolution is minimized. When biological processes are included as part of the treatment, the pH is lowered to more neutral conditions by carbon dioxide so evolved [42].

2.3.4. Chromium Compounds

Metal compounds are not biodegradable. They can thus be regarded as long term environmental features. Since they can also have accumulative properties, they are the subjects of close attention. Two forms of chrome are associated with the tanning industry, whose properties are often confused.

2.3.4.1. Chrome^{3+} (Trivalent Chrome, Chrome III)

Chromium is mainly found in waste from the chrome tanning process; it occurs as part of the retanning system and is displaced from leathers during retanning and dyeing processes. This chrome is discharged from processes in soluble form; however, when mixed with tannery waste waters from other processes (especially if proteins are present), the reaction is very rapid. Precipitates are formed, mainly protein-chrome, which add to sludge generation. However, very fine colloids are also formed which are then stabilised by the chrome - in effect, the protein has been partially tanned. The components are thus highly resistant to biological breakdown, and the biological process in both surface waters and treatment plants is inhibited. Once successfully broken down, chromium hydroxide precipitates and persists in the ecosystem for an extended period of time. If chrome discharges are excessive, the chromium might remain in the solution. Even in low concentrations, it has a toxic effect upon daphnia, thus disrupting the food chain for fish life and possibly inhibiting photosynthesis. Chrome levels can be determined in a number of ways. The first stage, however, usually comprises boiling a known volume of sample with concentrated nitric acid to ensure complete solution of the chrome. After suitable dilution, the chromium level is determined by atomic absorption. Where high levels of chrome are expected, iodine/thiosulphate titrations are sometimes used. That technique, however, is inaccurate at low concentrations [48] [45].

2.3.4.2. Chrome^{6+} (Hexavalent Chrome, Chrome VI)

Tannery effluents are unlikely to contain chromium in this form. Dichromats are toxic to fish life since they swiftly penetrate cell walls. They are mainly absorbed through the gills and the effect is accumulative. Analysis is highly specialized. The concentrations normally anticipated are very low and analysis is based on colorimetric measurement at 670 nm [42] [45].

2.3.5. Other Metals

Other metals which might be discharged from tanneries and whose discharge may be subject to statutory limits include aluminum and zirconium. Depending on the chemical species, these metals have differing toxicities that are also affected by the presence of other organic matter, complexing agents and the pH of the water. Aluminum, in particular, appears to inhibit the growth of green algae and crustaceans are sensitive to low concentrations. Cadmium, sometimes used in yellow pigments, is considered highly toxic. It is accumulative and has a chronic effect on a wide range of organisms.

2.3.6. Solvents

Solvents originate from degreasing and finishing operations. Solvents in effluents discharged to surface waters can form a microfilm on the water surface, thus inhibiting the uptake of oxygen.

Solvents break down in a variety of ways; some inhibit bacterial activity and remain in the eco-system for extended periods of time. Analysis is highly specialized.

2.3.7. Toxicity

A measure of toxicity can be expressed as LD_{50}, representing the dose which will kill 50% of a sample species. Not every species reacts to the same degree to a given exposure, and the type of response to an equal dose of a chemical may differ widely. When values are given, the species under test should be stated and the time period taken for evaluation should normally be 24 or 96 hours or 14 days. The toxicity of many metals also varies according to the pH level, temperature and water hardness.

Where Cr^{3}+ is concerned, investigations have been performed on fish (unspecified) under conditions of exposure insufficient to cause severe toxicity, yet sufficient to cause visible changes in behavior [48.50]. These dosages were 0.2 mg/l. It is understood however, that daphnia are even more susceptible, thus posing a potential hazard to the food chain for fish. Although not used in leather processing, zinc and copper are described as having a 'high/acute' and 'chronic' toxic effect on aquatic life. The maximum levels are 0.3 mg/l total and 0.04 mg/l (dissolved) respectively as given in the standards set by the E.U in its Fish Directives for salmon. Similar toxicity definitions apply to Cr^{3+}, and it is stated that dosages of 0.2 mg/l induce behavioral change in fish (unspecified). In the absence of more specific data, loadings of this order might be considered maximum permissible values for surface waters.

No limits are set for COD, as substances (and toxicity) cannot be specified. Other limits found in the standards set by the E.U [49] [50] in its Fish Directives are presented below:

Suspended solids (SS) < 25 mg/l

Biological oxygen demand (BOD_5) < 5 mg/l

Ammonia (NH3) < 0.025 mg/l

Kjeldahl nitrogen (TKN) < 0.78 mg/l

There are no values for sulphides, but their presence is included in the BOD analysis.

2.4. National Effluent Quality Standards and International Legislation for Tannery Effluent

The Bangladesh standards intend to impose restrictions on the volume and concentrations of wastewater/solid waste/gaseous emission etc. discharged into the environment. In addition, a number of surrogate pollution parameters like Biochemical Oxygen Demand, or Chemical Oxygen Demand; Total Suspended Solids, etc. are specified in terms of concentration and/or total allowable quality discharged in case of waste water/solid waste.

The ambient standard of water quality, air quality and noise are presented in Table 5 taken from ECR Schedule 10 and Table 6 taken from ECR Schedule 3 [51]. Standards refer to discharges to freshwater bodies with values in parentheses referring to direct discharges to agricultural land in Bangladesh.

Table 5 :Inland surface quality standards for waste from industrial units *[51]*

Parameter	**Inland surface quality standards (mg/l)**
Temperature (ºC)	40
Biological Oxygen Demand (BOD5) at 20ºC	50
Chemical Oxygen Demand (COD)	200
Dissolved Oxygen (DO)	4.5-8
Total Dissolved Solids (TDS)	2,100
pH	6-9
Suspended Solid (SS)	150
Nitrate	10
Arsenic	0.2
Lead	0.1
Chloride	600
Iron	2
Manganese	5
Oil & Grease	10

Table 6 : Standards for drinking water *[51]*

Parameter	DoE (Bangladesh) standards for drinking water (mg/l)
pH	6.5-8.5
Hardness (as CaCO3)	200-500
Nitrate	10
Arsenic	0.05
Chloride	150-600
Iron	0.3-1.0
Residual Chlorine	0.2
Ammonia	0.5
Phosphate	6

In developing countries, according to the environmental pollution control regulations set by various national and international environment protection agencies, Tanneries are forced to set up the WWTPs either individually as ETP or collectively as CETP and the treated wastewater should comply with the discharge standards. The compliance with the discharge standards has not always been practical either because the laws are too ambitious or unrealistic in case of certain parameters, or they have lacked the effective instrumentation and institutional support. Some environment protection laws have not succeeded because they do not match the technical requirements and economic reality of the country or they do not have the institutional support to implement them into consideration. In India, during the 1990s, several Tanneries were ordered to close their units as these could not meet the discharge standards, while many of them paid huge compensation for the damage caused due to the groundwater contamination [52].

For the sake of tanneries, the Bangladesh government has offered to construct Common Effluent Treatment Plants (CETP) for the treatment of tannery effluent. Notwithstanding, the pollution problems are still common due to high operation and management cost associated with CETP and thus causing illegal dumping of wastewater [53]. In Uganda, the main leather industry was found to dump its wastewater directly into a wetland adjacent to Lake Victoria [54] whereas in Croatia, the pollution abatement cost exceeded the compensation cost against the irresponsible behavior of tanneries. The environmental pollution due to the discharge of tannery effluent has become a serious concern in recent years. For pollution prevention from tannery effluent and its chemicals, the United Nations Industrial Development Organization (UNIDO) has compiled the standard limits for the discharge of tannery effluent into water bodies and sewers from several countries worldwide [46] [47]. The discharge standards for some of the countries are presented in Table A1, A2 and A3 (See Appendix A). The discharge limits for tannery effluent may vary from country to country and are either related to the quality of treated wastewater or the quality of receiving water bodies [45].

2.5. Concept of Water Footprint

The idea of considering water use along supply chains has gained interest after the introduction of the concept of "water footprint" introduced by Hoekstra (2003) [55] and subsequently elaborated by Hoekstra and Chapagain (2008) [56] which provided a framework to analyze the link between human consumption and the appropriation of the globe's freshwater. The water footprint is an indicator of freshwater use that looks not only at direct water use of a consumer or producer, but also at the indirect water use.

The water footprint can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. The water footprint of a product (alternatively known as "virtual water content") expressed in water volume per unit of product (usually m^3/ton) is the sum of the water footprints of the process steps taken to produce the product [57]. Total water footprint of product includes blue water footprint, green water footprint and grey water footprint.

2.5.1. Blue Water Footprint

The blue water footprint is an indicator of consumptive use of so-called blue water, i.e. fresh surface or groundwater [58]. The term 'consumptive water use' refers to one of the following four cases:

- water evaporates;
- water is incorporated into the product;

- water does not return to the same catchment area, e.g. it is returned to another catchment area or the sea;
- water does not return in the same period, e.g. it is withdrawn in a scarce period and returned in a wet period.

for manufacturing processes, one can rely on databases that contain typical data on consumptive water use per type of manufacturing process.

2.5.2. Green Water Footprint

The green water footprint is the volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (products based on crops or wood), where it refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood [58].

2.5.3. Grey Water Footprint

The grey water footprint of a process step is an indicator of the degree of freshwater pollution that can be associated with the process step. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. It is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards [59] [58]. The grey water footprint, expressed as a dilution water requirement, has been recognized earlier by [60] [61]. Including the grey water footprint is relatively new in water use studies, but justified when considering the relevance of pollution as a driver of water scarcity.

Chapter 3: Methodology and Data

3.1. Experimental Analysis of Pollutants

To calculate grey water footprint and pollution load of leather production intensive experiments have been conducted in Environment lab, Chemical Engineering Department, BUET. The sample has been collected from the four tanneries waste water from each stage of the leather production. Four tanneries are selected by the consultation of leather technologist. After careful collection of the samples, they are preserved by freezing. Then the samples are carefully preserved in the Environment lab and analyzed accordingly. The experiments are conducted to analyze pH value, BOD_5, COD, TDS, TSS of the effluent.

3.1.1. pH:

pH has been calculated by HANNA pH Meter, HI 2211 pH/mV Meter. Fresh samples are taken in 100 ml beaker after rinsing and then data has been taken.

3.1.2. Biological Oxidation Demand (BOD_5):

BOD_5 has been measured using standard method 5210B. To calculate BOD sample are prepared with all the BOD reagents and Bacterial seed with distill water with 100:1 amount in 500 ml BOD bottles. Then DO data has been collected by HANNA DO Meter and then incubated in 25^{o}C for 5 days. Another DO data are collected after 5 days. Then using eq 19 the BOD value has been calculated. Here f is bacterial factor and V is volume of the sample.

$$BOD = [(DO\ sample - DO_5\ sample) - (DO\ blank - DO_5\ blank)] \times (f/V) \quad \ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots (1)$$

3.1.3. Chemical Oxidation Demand (COD):

To calculate COD, the samples are prepared with the COD reagents and sulphuric acid (H_2SO_4) in 10 ml tube. Then sample tubes are digested for 2 hours in 120^{o}C. After completing the digestion, the tubes are cooled and data are collected from HACH spectrophotometer, DR-6000 in the lab. Data need correction so COD values from spectrophotometer are corrected by correction factor.

3.1.4. Total Dissolve Solid (TDS)

The TDS data are collected by HANNA TDS Meter. Fresh samples are taken in 100 ml beaker after rinsing and then data has been taken.

3.1.5. Total Suspended Solid (TSS):

To calculate TSS, the Hot bath method are selected as the TDS value was very high. Samples are taken in 100 ml beaker and measured their weight then put them in Hot bath for 24 hours. Then samples are collected and put it in desiccator until the beaker cooled down. Then another weight of beaker with sample has been taken. Then difference of weight of sample gives the Total Solid (TS). The deference of TS and TDS is the value of TSS.

Estimated Weight of Animal products

For calculating pollution load each year weight of animal products is used as basis. Weight of animal products has been calculated from export value of leather from export promotion bureau (EPB) [12] and then it converted into weight of crust, wet blue, pelt and raw hides with back calculation of their specific weight (raw hide 0.737 kg/ft^2, pelt 0.474 kg/ft^2, wet blue 0.211 kg/ft^2, crust 0.10 kg/ft^2) [28]. In table 7 the estimated weights of animal products are given from FY 2013 to FY 2017.

Table 7: Estimated weight of animal products hide, pelt, wet blue and crust leather

Year	Total production of crust leather ($\times 10^4$) (ton/ year)	Total production of wet blue shaved leather ($\times 10^4$) (ton/ year)	Total production of pelt leather ($\times 10^5$) (ton/ year)	Total production raw hide ($\times 10^5$) (ton/ year)
FY: 2013	3.66	7.70	1.73	2.69
FY: 2014	4.65	9.79	2.20	3.43
FY: 2015	3.86	8.12	1.83	2.84
FY: 2016	3.00	6.32	1.42	2.21
FY: 2017	2.73	5.74	1.29	2.01

3.2. Methodology for Water Footprint Calculation of Leather

The water footprint of a product is the sum of the water footprints of the process steps taken to produce the product (considering the whole production and supply chain). For calculating the water footprint of leather every water footprint involve in leather production needs to be calculated. All the water footprints calculation methodology has been described below.

$WF = WF_{blue} + WF_{green} + WF_{grey}$ ………………………………………………………… (2)

$WF = WF_{direct} + WF_{indirect}$ ………………………………..…………………………….……… (3)

3.2.1. Water Footprint Calculation of Feed Crops

The green, blue and grey water footprints of crop production were estimated following the calculation framework of Hoekstra et al. (2011) [58]. The computations of crop evapotranspiration and yield, required for the estimation of the green and blue water footprint in crop production, have been done following the method and assumptions provided by Allen et al. (1998) [62].

3.2.1.1. Blue and Green Water Footprint of Feed crops

for the case of crop growth under non-optimal conditions. The grid-based dynamic water balance model used in the study computes a daily soil water balance and calculates crop water requirements, actual crop water use (both green and blue) and actual yields. Feed crops, which are grown in Bangladesh, the CROPWAT 8.0 model is used.

Reference Evapotranspiration (ET_o) Calculation: Reference evapotranspiration (ET_o) is the water evaporated from a reference surface, and was presented to quantify evaporative demand of the atmosphere, independent of the crop growth parameters and management practices [62] [58] and important to calculate crops water requirement (CWR). For this model Penman Monteith formula (equation 4) has been used where the reference ET_0 values were estimated using FAO 56 PM for each of the stations [63]. The FAO56 PM is a hypothetical grass reference based model that have following characteristics: mean height of vegetation (h)=0.12 m, measurement of temperature, humidity, and wind at the height of 2 m, latent heat transfer (λ)=2.45(MJ kg^{-1}), bulk surface resistance of 70 sm^{-1}, and albedo=0.23. The final form of the FAO 56 PM equation for daily or monthly time step is defined as [62].

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T+273} u^2 (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u^2)} \quad \text{……………………………………………………. (4)}$$

Here,

ET_0 = reference evapotranspiration (mm d^{-1}),

R_n= net radiation (MJ m^{-2} d^{-1}),

$e_S - e_a$= difference between the saturation vapor pressure e_S (kPa) and the actual vapor pressure e_a (kPa),

Δ= slope of the saturation vapor pressure–temperature curve (kPa °C^{-1}),

γ= psychrometric constant (kPa °C^{-1}),

u^2= wind speed at 2 m height (m s^{-1}),

T= mean daily air temperature (°C),

G= monthly soil heat flux density (MJ m^{-2} d^{-1}).

All the intermediate parameters were computed following Allen et al. (1998) [62].

Effective Precipitation (P_{eff}) Calculation: The evaluation of effective rainfall involves measuring rainfall and/or irrigation, losses toy surface run-off, percolation losses beyond the root zone and the soil moisture uptake by the crop for evapotranspiration [64]. The USDA SCS (United States Department of Agriculture Soil Conservation Service) method has been used to estimate the effective rainfall (Eq 5, Eq 6) in CROPWAT 8.0 model.

$P_{eff} = (P \times (125 - 0.2 \times 3 \text{ X } P))/ 125$ for P <= 250/3 ……………………………… (5)

$P_{eff} = 125/3 + 0.1 \text{ X } P$ for P> 250/3 ……………………………… (6)

Crop Water Demand and Water Available Graphs: Above mentioned Evapotranspiration (ET), Effective Rainfall (P_{eff}), Crop data, soil data helps to calculate the crop water requirement (CWR). Crop water requirement (CWR) generates water demand (WD) versus Water available (WA) graphs.

The water use in the crop fields is calculated for each 10 days cumulative period using the schema as presented in Figure 08. If the total water demand WD is less than total water available WA, green water use is equal to the demand WD. In cases where the WD outstrips WA, the deficit is met by irrigation water supply. This deficit is called irrigation water demand. If a paddy field is 100% irrigated, it is assumed that the 'blue water' use in crop production is equal to the deficit. For areas equipped with partial irrigation coverage, the blue water use is estimated on a pro-rata basis.

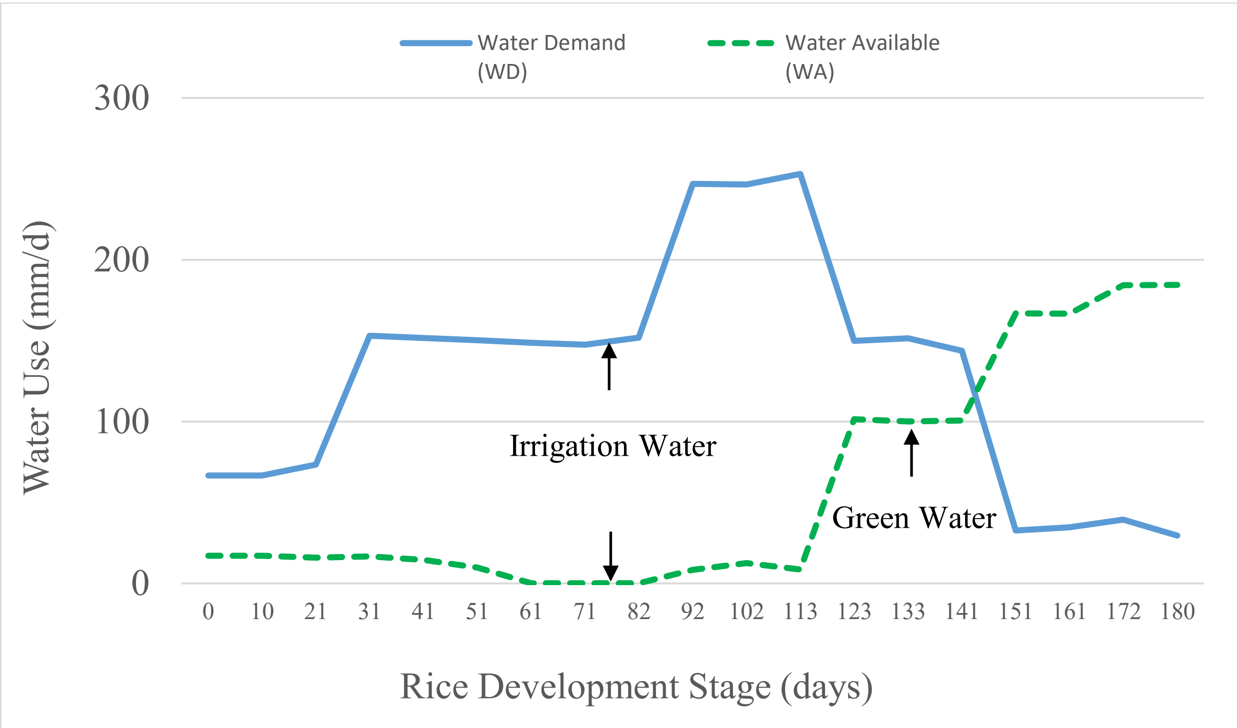


Figure 8: Graphical representation of water demand and water available for rice

Rice needs irrigation water in its mid stage shown in figure 8. But the grass in Bangladesh does not require irrigation as it gets enough water from rainfall for the growth. So, pasture has only green water use which has shown in figure 9. Wheat also requires irrigation water in its mid stage of development (See figure 10). Maize has larger irrigation requirement than pulses on the other hand pulses have larger green water use than maize which is given in the figure 11 and 12.

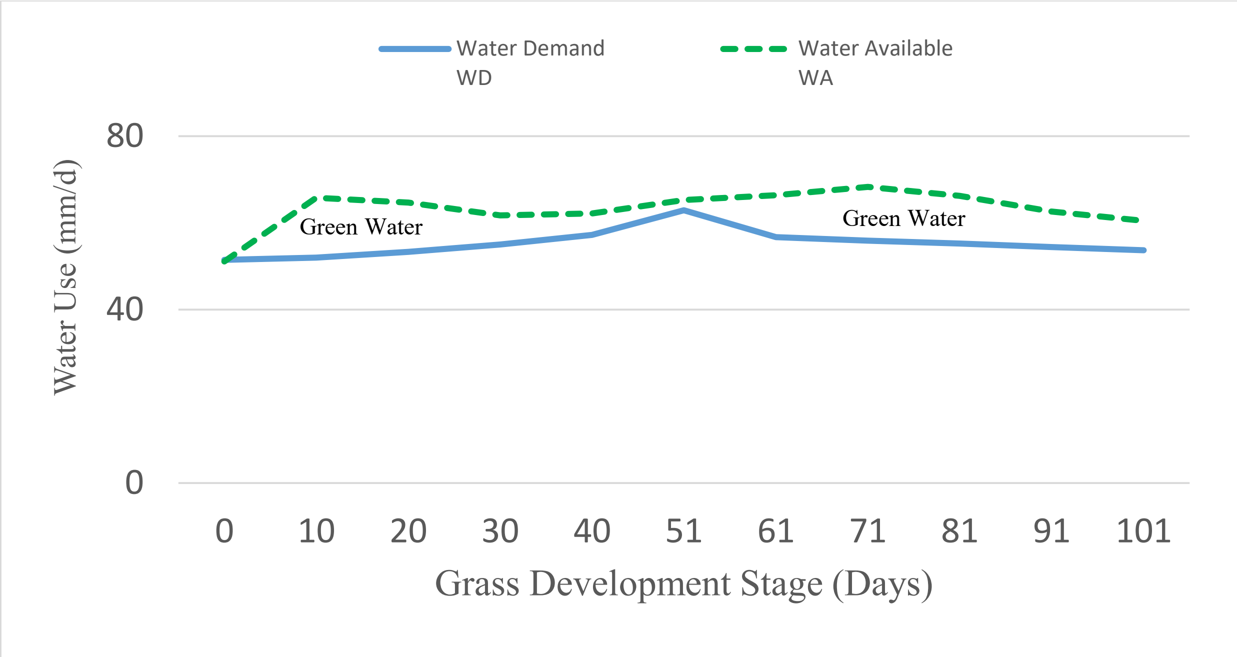


Figure 9: Graphical representation of water demand and water available for pasture

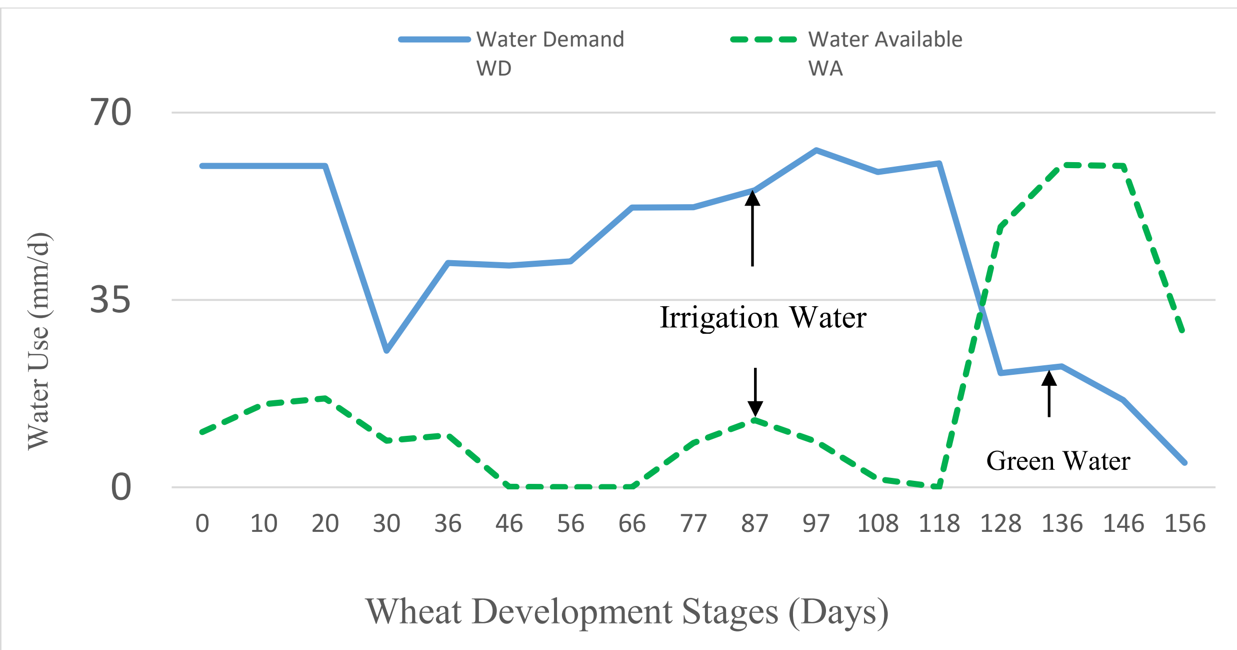


Figure 10: Graphical representation of water demand and water available for wheat

Maize needs irrigation in its mid stage but water amount is less than rice and wheat shown in figure 11. On the other hand, pulses need irrigation in last stage (see figure 12) but Bangladesh has many variations of pulses so here the average irrigation water has been considered.

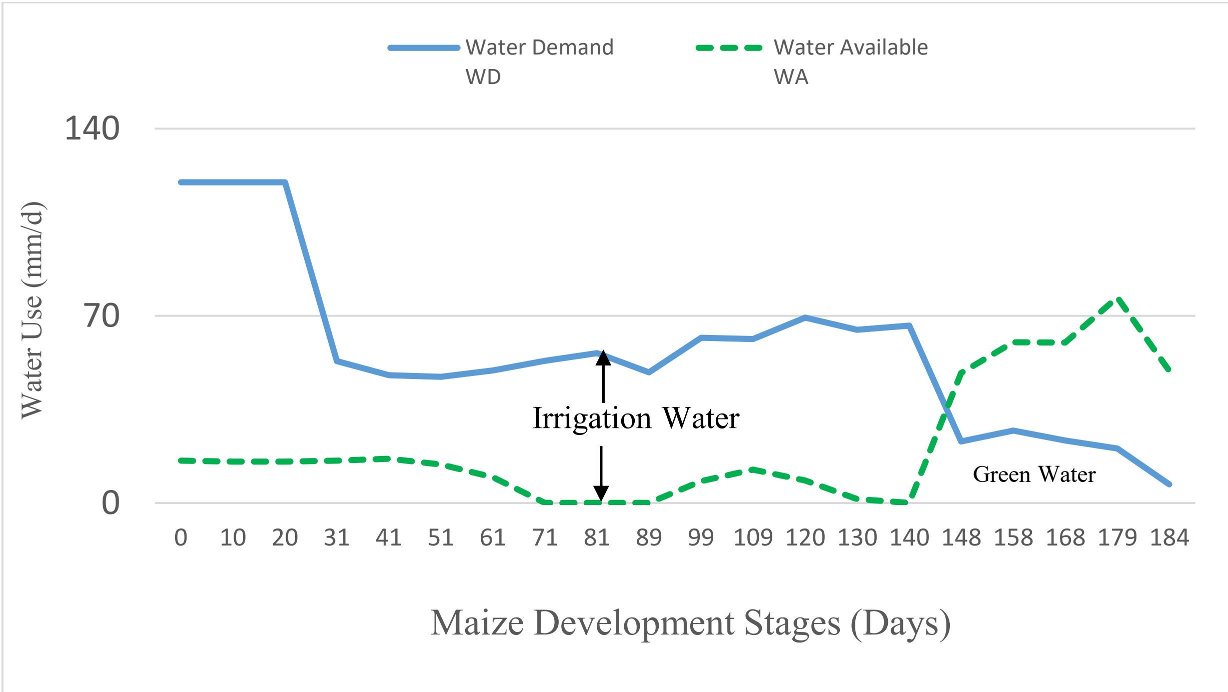


Figure 11: Graphical representation of water demand and water available for maize

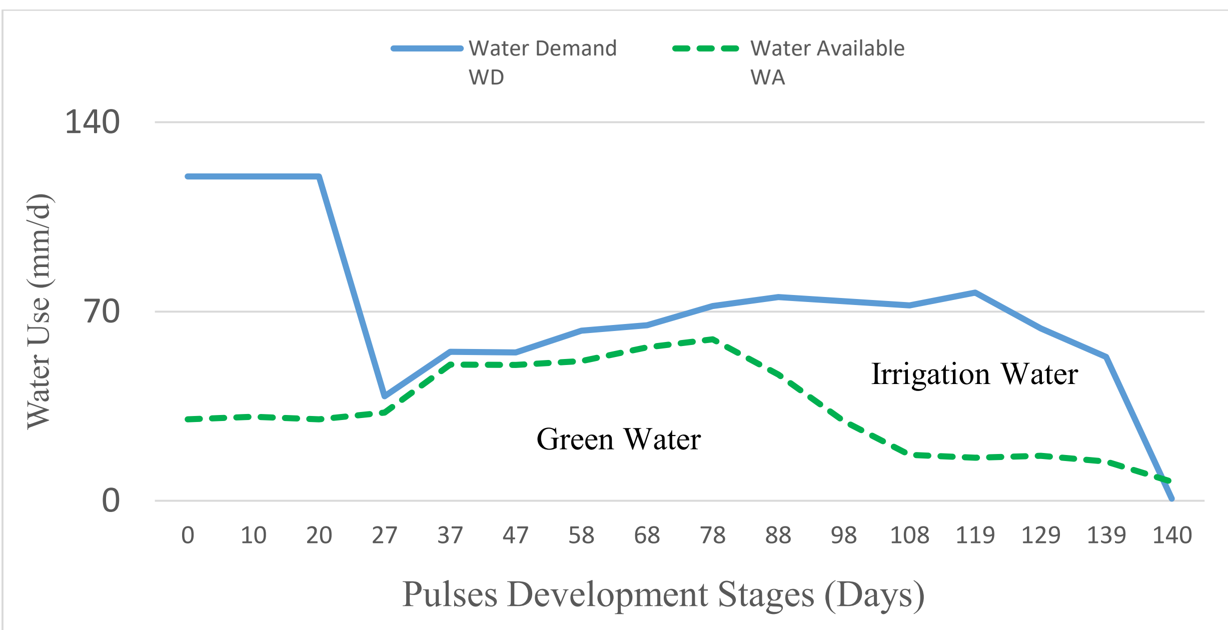


Figure 12: Graphical representation of water demand and water available for pulses

Crop Water Depth (CWD), Crop Water Use (CWU) Calculation: The irrigation requirement (*IR*) or Blue Crop water depth (CWD_{blue}) is calculated as the difference between crop Water Demand (WD) and Water Available (WA) which is equation 7. The irrigation requirement is zero if effective rainfall or Water Available is larger than the crop water requirement or Water Demand [8]. This means:

$$IR = \max(0, WD - WA) \quad (7)$$

It is assumed that the irrigation requirements are fully met. Green Crop water Depth (CWD_{green}), i.e. Water Use of rainfall, can be equated with the minimum of total crop evapotranspiration (*ETc*) and effective rainfall (P_{eff}). Blue Crop water depth (CWD_{blue}), i.e., field-evapotranspiration of irrigation water, is equal to the total Water demand (WD) minus Water available (*WA*), but zero when effective rainfall exceeds water demand (WD) and equation 8 and 9 are used [8] [65]:

$$CWD_{green} = \min(WD, P_{eff}) \quad (8)$$

$$CWD_{blue} = \max(0, IR\ (WD\text{-}WA)) \quad (9)$$

All water flows are expressed in mm/day or in mm per period of simulation (e.g., ten days). The average irrigation water requirement and green water use are calculated based on the data for the major district in Bangladesh. Blue water use is calculated by multiplying the irrigation requirement with the irrigated area in each season per district [65]. The green water use in irrigated areas is calculated by multiplying the green water depth by the total area in each season.

The water footprint is the volume of water used to produce a particular good, measured at the point of production [65] [66] [67] [68] [69] [70]. So, the green and blue water footprints of primary crop by product and crop residue ($m^3\ ton^{-1}$) are calculated by dividing the total volume of green and blue water use, CWU ($m^3\ yr^{-1}$), respectively, by the quantity of the production ($ton\ yr^{-1}$).

3.2.1.2. Grey Water Footprint of Feed Crop

Grey water footprint (GWF) indicates the volume of fresh water is needed to assimilate the pollutant load in the water body [8] [58]. GWF can be calculated by dividing the pollutant load entering into the water body (L, mass/time) by critical load ($L_{critical}$, mass/time) times run off of the water body (R, volume/time).

$$WF_{grey}= \frac{L}{L_{crit}} \times R \qquad (10)$$

Critical load, $L_{critical}$ refers to the total capacity of the receiving water body to consume the pollutant load. It can be calculated from the ambient water quality standard [51]. It is the subtraction of maximum concentration (C_{max}) from the natural concentration (C_{nat}) of pollutant in the water times the run off (R) of the water body [8].

$$L_{critical}= R\times (C_{max} - C_{nat}) \qquad (11)$$

So, the equation becomes like this

$$WF_{grey}= \frac{L}{C_{max}-C_{nat}} \qquad (12)$$

For the diffuse source the calculation of the pollutant load of the water body is not so straight forward because the chemicals like fertilizers, pesticides or solid waste disposal are entering into the surface water and ground water in a diffuse way. So, it is assumed that a fraction (f) of the applied chemicals reaches to the ground water or surface water [71] [72]. So, the calculation of the load becomes fraction multiplied by application rate (Appl).

$$L = f \times Appl \text{ (mass/ time)} \qquad (13)$$

The estimation of the leaching-runoff fraction (f) is also not so straight forward. At tier 1 estimating f is mostly qualitative information about environmental factors and agricultural practices. But at tier 2[1] and 3[2] estimating of fraction f is the study of different chemical process and pathways [72].

$$\text{Here, } f = f_{min} + \frac{\sum Si \times Wi}{\sum Wi} \times (f_{max} - f_{min}) \quad \dots\dots (14)$$

Fraction f can be estimated using the equation mentioned above. The maximum and the minimum concentration have been taken from Table 10. Per factor the score for the leaching run off potential (S) is multiplied by the weight factor (W). Score (S) and Weight (W) of leaching and runoff fraction depends on the environmental factors such as soil type in case of rice soil type clayey [65], for maize its sandy loamy to loamy [73], for wheat it can be loamy [74]. Application rate of the fertilizers of rice [73], maize [75] and wheat [73] in Bangladesh can be taken from the data available. Fertilizers mostly are urea, TSP, mixed, gypsum etc.

The water footprint of a farm animal is related to the feed consumed consists of two parts: the water footprint of the various feed ingredients and the water that is used to mix the feed:

$$WF_{feed}[a,c,s] = \frac{\sum_{p=1}^{n}\left(Feed[a,c,s,p] \times WF_{prod}^{*}[p]\right) + WF_{mixing}[a,c,s]}{Pop^{*}[a,c,s]} \quad \dots\dots (15)$$

The water footprints of the different crops, roughages and crop by-products (WF_{prod*} [p], m^3/ton) that are eaten by the various farm animals have been calculated following the methodology developed by Hoekstra and Chapagain [81] and Hoekstra and others [58]. The water footprints of feed crops were estimated using a crop water use model that estimates crop water footprints [82]

[1] Tier 2 applies standardized and simplified model approaches and can be used based on relatively easily obtainable data (such as the chemical properties of the chemical substance considered and the topographic, climatic, hydrologic and soil characteristics of the environment in which the chemical substance is applied). These simple and standardized model approaches should be derived from more advanced and validated models

[2] Tier 3 uses sophisticated modeling techniques and/or intensive measurement approaches. Since this approach is very laborious, available resources should allow for it and the purpose of application should warrant it. Whereas detailed physically-based models of contaminant flows through soils are available, their complexity often renders them inappropriate even for use at tier-3 level. However, validated empirical models driven by information on farm practices and data on soil and weather characteristics are presently available for use in diffuse-load studies at this level.

[71]. Grey water footprints were estimated by looking at leaching and runoff of nitrogen-fertilizers only, following Mekonnen and Hoekstra [71]. As animal feed in a country originates from domestic production and imported products, for the calculation of the water footprint of animal feed in a country, we have taken a weighted average water footprint according to the relative volumes of domestic production and import:

$$WF^*_{Prod}[p] = \frac{P[p] \times WF_{prod}[p] + \sum_{n_e} (T_i[n_e,p] \times WF_{prod}[n_e,p])}{P[p] + \sum_{n_e} T_i[n_e,p]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

in which P[p] is the production quantity of feed product p in a country (ton/y), $T_i[n_e,p]$ the imported quantity of feed product p from exporting nation n_e (ton/y), $WF_{prod}[p]$ the water footprint of feed product p when produced in the nation considered (m^3/ton) and $WF_{prod}[n_e,p]$ the water footprint of feed product p as in the exporting nation n_e (m^3/ton). The water footprint of crop residues such as bran, straw and leaves have already been accounted for in the main product, therefore their water footprint was calculated from it. Bangladesh does not import animal foods from other countries. Animal feed has been considered domestic production ($T_i = 0$).

The total feed per production system for both ruminants and non-ruminant animals is calculated as follows (eq 18):

$$\text{Feed}[a; c; s] = \text{FCE}[a; c; s] \times P[a; c; s] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

where Feed[a,c,s] is the total amount of feed consumed by animal category a (ton/y) in country c and production system s, FCE[a,c,s] the feed conversion efficiency (kg dry mass of feed/kg of product) for animal category a in country c and production system s, and P[a,c,s] the total amount of product (hides & skins) produced by animal category a (cattle or goat) (ton/y) in country c (Bangladesh) and production system s (extensive and semi-extensive).

3.2.1.3. Necessary Data Collection for Feed crop: Calculating water footprint require data includes climate monthly data, Soil data and crops cultivation data of Bangladesh. The calculation should be done using climate data from the nearest and most representative meteorological station(s) located near the crop field considered or within or near the crop-producing district considered. Selected meteorological station for this research are Barisal, Bogra Comilla, Chittagong, Dhaka, Dinajpur, Faridpur, Jessore, Khulna, Mymensingh, Patuakhali, Rajshahi, Rangpur, Sylhet and Tangail. Data are being discussed below:

Climate Data: Monthly climate data includes humidity (See Table B1, B 2), wind (See Table B9, B10), maximum temperature (See Table B5, B6), minimum temperature (See Table B3, B4), rainfall (See Table B7, B8) of the selected weather station of Bangladesh (See Appendix B). Data has been taken from yearbook of agricultural statistics 2016 released from Bangladesh Bureau of Statistics (BBS), Ministry of Planning Division [76].

Crop Data: Crop coefficients and cropping pattern (planting and harvesting dates) can best be taken from local data. The crop variety and suitable growing period for a particular type of crop largely depends upon the climate. The crop coefficient varies in time, as a function of the plant growth stage. During the initial and mid-season stages, Kc is a constant and equals Kc,ini and Kc,mid respectively. During the crop development stage, Kc is assumed to linearly increase from Kc,ini to Kc,mid. In the late season stage, Kc is assumed to decrease linearly from Kc,mid to Kc,end. Crop planting dates and lengths of cropping seasons were given in table B11 and table B12 (See Appendix B) [77] [78] [79].

Soil Data: Soil texture data are included in this CROPWAT 8.0 model. Bangladesh has soil texture of Clay Loam (Barishal, Bogra, jessore, Jamalpur, Tangail), Loam (Comilla, Dinajpur, Gazipur, Sylhet), Sandy clay loam (Chittagong, Dinajpur, Rangpur), Silty loam (Dhaka), Clay (Faridpur, Khulna, Patukhali, Shatkhira) (See Table 8) [80].

Table 8: Soil texture of selected meteorological stations of Bangladesh *[80]*

Station	Soil texture
Barishal	Clay Loam
Bogra	Clay Loam
Comilla	Loam
Ctg	Sandy Clay Loam
Dhaka	Silty Loam
Dinajpur	Sandy Clay Loam, Loam
Faridpur	Clay
Jessore	Clay Loam
Khulna	Clay
Mymensingh	Sandy loam, Loam, Clay Loam
Patuakhali	Clay
Rajshahi	Loam, Clay Loam
Rangpur	Sandy clay Loam
Sylhet	Loam
Maoulavi bazar	Sandy Clay Loam, Sandy Loam
Jamalpur	Clay Loam
Tangail	Clay Loam
Gazipur	Loam
Shatkhira	Clay

Fertilizer Application Rate: In Bangladesh cultivable land is limited but used frequently. The fertilizer application rate of feed crops has been obtained from the Handbook of Agricultural Technology released from Bangladesh Agricultural Research Council (BARC) and Asian Food and Agricultural Cooperation Initiative (AFACI) [73]. Mostly local fertilizer cow dung is used other than Urea, TSP, MP, Gypsum etc. are equally popular (See Table 9). But Grass as feed crop has no fertilizer application in Bangladesh.

Table 9: Fertilizer application rate in selected crop cultivation of Bangladesh *[73] [75]*

Crop Category	Fertilizer	Application rate (kg/ha)
Rice	Cow dung	20000
	Urea	300
	TSP	97
	MP	120
	Gypsum	112
	Zinc	10
Wheat	Urea	220
	TSP	150
	MP	100
	Gypsum	100
	Borax	6.5
	Lime (Dolomite)[3]	1000
Maize	Cow dung	5.5
	Urea	464
	TSP	144
	MP	113
	Mixed	100
	Gypsum	89
	Zinc	8
	Borax	4
	Lime	87
	Insecticides	352
Pulse	Urea	44
	TSP	100
	MP	40
	Boric Acid	7.5

Leaching Fraction: As fertilizer pollutants comes from diffuse sources there are certain protocols have to follow. The leaching and run off data for different fertilizer component (i.e. Nitrogen, Phosphorous) has to estimate through certain factors (See Table 10). The data of leaching run off fraction also depends on climate and agricultural practices and its component nitrogen (See Table B13), phosphorous (See Table B14) and Metal (See Table B15) [72].

[3] Once in Three Year

Table 10: Minimum, average and maximum leaching-run off fraction *[72]*

Leaching-runoff fraction	Nutrient		Metals	Pesticides
	Nitrogen	Phosphorus		
Minimum, f_{min}	0.01	0.0001	0.4	0.0001
Average, f_{avg}	0.1	0.03	0.7	0.01
Maximum, f_{max}	0.25	0.05	0.9	0.1

Ambient Water Quality Standard and Natural Concentrations of Pollutants: Bangladesh Ambient Water Quality Standard and Natural Concentrations of pollutants has been discussed in section 2.4 [51]. Water quality standard of Bangladesh has been given by Department of Environment (DoE) of Bangladesh in Table 5 and Table 6.

3.2.2. Water Footprint of Hides and Skins

The water footprint of a live animal (e.g., cattle, buffalo, goat and sheep) consists of different components: the indirect water footprint of the feed and the direct water footprint related to the drinking water and service water consumed, method followed as [8]. The water footprint of an animal is expressed as:

$$WF_{Animal}\,[a; c; s] = WF_{feed}\,[a; c; s] + WF_{drink}\,[a; c; s] + WF_{serv}\,[a; c; s] \quad \ldots\ldots\ldots\ldots (18)$$

where $WF_{feed}[a,c,s]$, $WF_{drink}[a,c,s]$ and $WF_{serv}[a,c,s]$ represent the water footprint of an animal for animal category a in country; c in production systems s related to feed, drinking water and service-water consumption, respectively. Service water refers to the water used to clean the farmyard, wash the animal and carry out other services necessary to maintain the environment. The water footprint of a farm animal and its three components can be expressed in terms of m^3/y/animal, or, when summed over the lifetime of the animal, in terms of m^3/animal.

Water footprint of hide changes country to country as the climate, culture and management system of livestock are different in each country. The objective of this research is very clear to calculate the water footprint of leather for Bangladesh. So, all data and criteria to calculate the water footprint of hide and skin are based on livestock of Bangladesh.

Here, Animal category, a = Cattle and Goat

Country, c = Bangladesh

Production system, s = Extensive and grazing

Then water footprint of animal converted into hide using with the equation 19.

$$WF_{Product} = \frac{WF_{Animal[a,c,s]} \times W_{Animal} \times DP \times P_f}{W_{product}} \quad \text{(19)}$$

Where DP is dressing percentage and P_f is product fraction, W_{Animal} is weight of live animal and $W_{Product}$ is weight of product. For this study considered animals are cattle and goat. And the dressing percentage and product fraction of hides are calculated using the equation 20, 21.

$$DP\ (\%) = \frac{\text{Chilled carcass weight}}{\text{Live weight during slaughtering}} \times 100 \quad \text{(20)}$$

$$P_f = \frac{W_{product}}{W_{animal}} \quad \text{(21)}$$

Product fraction (P_f) has been taken 8.4% [83] for cattle and 11% [84] for goat from livestock data. Water for mixing with the food intake has been taken 2 L/kg. Servicing water has been assumed 28 L/kg. Drinking water has been estimated 120 L/kg for cattle and 87 L/kg for goat [85]. All the data required for the water footprint of hide are mentioned in table 11.

Specification for selected cattle for this study

Medium farmer category

Market age (month) = 36

Live Weight (kg) = 178

Specification for selected goat for this study

Small farmer category

Market age (month) = 15.5

Live Weight (kg) = 17.10

Different research groups used value fraction to calculate water footprint of any specific part of an animal. Value fraction is referred to as the market value of one product from the animal as descried in Aldaya et al [58]. However, the correlation between market value (e.g., US$ or BDT) and water footprint of any specific part of an animal is not well defined and well understood. Therefore, in this study instead of value fraction, product fraction is used to convert the water footprint from animal to hide. To calculate value fraction additional equation is needed.

$$V_f = \frac{V \times P_f}{\Sigma V \times P_f} \quad (22)$$

Here method taking value fraction and without taking value fraction is given.

Method with value fraction:

Live weight of cattle (W_{Animal}) = 178 kg

As dressing percentage (DP) = 54% So, Weight of carcass ($W_{Carcass}$) = 96 kg

Product fraction of hide (P_f) = 8.4% So, Weight of hide ($W_{Product}$) = 15 kg

Assuming Value fraction (V_f) = 5%

Total water footprint of cattle, WF_{Animal} = 45682 L/kg carcass

Total water footprint of cattle, WF_{Animal} = 45682 × 96

= 4385515 L

So, Total water footprint of cattle, WF_{Animal} = 24638 L/kg

Total water footprint of hide, $WF_{Product} = \frac{WF_{Animal} \times V_f}{W_{Product}}$

$= \frac{4385515 \times 0.05}{15}$

= 14618 L/kg

Method with product fraction (without value fraction):

Live weight of cattle, (W_{Animal}) = 178 kg

As dressing percentage, (DP) = 54% So, Weight of carcass ($W_{carcass}$) = 96 kg

Product fraction of hide (P_f) = 8.4% So, Weight of hide ($W_{Product}$) = 15 kg

Total water footprint of cattle, WF_{Animal} = 45682 L/kg carcass

Total water footprint of cattle, WF_{Animal} = 45682 × 96

= 4385515 L

So, Total water footprint of cattle, WF_{Animal} = 24638 L/kg

Total water footprint of hide, $WF_{Product} = \frac{WF_{Animal} \times P_f}{W_{Product}}$

$$= \frac{4385515 \times 0.084}{15}$$

= 24559 L/kg

The equation for total water footprint of hide is similar to the equation 19 mentioned above. So, the method with product fraction (without value fraction) is considered for the calculation of the water footprint of leather.

Table 11: Necessary information for calculating the water footprint of hides and skins *[83] [86] [85]*

Information required	Cattle	Goat
Average daily drinking water (L/day)	27.70	2.70
Average daily servicing water (L/day)	6.40	6.40
Product fraction, P_f (%)	8.40	11
Dressing percentage, DP (%)	54	42
Weight of animal, W_{Animal} (kg)	178	7.30
Weight of hides, W_{Hide} (kg)	15.50	1.90
Water requires for mixing (L/kg)	2	2

Estimating the Total Annual Production of Hide and Skin

The annual production of animal product (hide and skin) has been estimated. The hide production (P_{Hide}, ton/yr) per animal category *a* (beef cattle, Buffaloes, sheep and goat) in country *c* (Bangladesh) and production system s (Extensive or semi extensive) is estimated by the annual export data [12] of leather, leather products and footwear has been discussed in the section 2.1. Export data of leather as shown in Figure 2 are converted into crust leather area then total production of crust leather in weight (See table 12). Then wet blue weight then pelts and finally hides and skins weight has been estimated with the conversion factors of area to weight which has been explained in section 3.1.

Table 12: Estimated weight of animal products hides and skins

Year	Total production raw hide ($\times 10^5$) (ton/ year)
FY: 2013	2.69
FY: 2014	3.43
FY: 2015	2.84
FY: 2016	2.21
FY: 2017	2.01

Estimating the Feed Composition

The volume of concentrate feed has been estimated per animal category and per production system. The composition of concentrate feeds varies across animal species and regions. Bangladesh has large population of Cattle, buffalo, goat and sheep and their feed composition is also limited within pasture, fodder and forages [87]. Three main categories of feed resources are potentially available for use in smallholder crop–animal systems in the country. These are pastures (native and improved grasses, herbaceous legumes and multi-purpose trees), crop residues, agro-industrial by-products [88]. Cattle and Buffalo have feed as pasture (58%), rice straw (21%), rice polish (8%), broken rice (3%), wheat bran (5%), pulse bran (3%), mustard and oilcake (2%) etc. (See figure 14) in Bangladesh. Goat and sheep have feed natural grass and leaves and concentrate (See figure 13). Comparatively Cattle and buffalo consume larger amount of feed crops than goat and sheep (See figure 15). In table 13 and table 14 feed crop residue and feed crop by product production, yield, availability has been given as Bangladesh Bureau of Statistic (BBS) has data released [76].

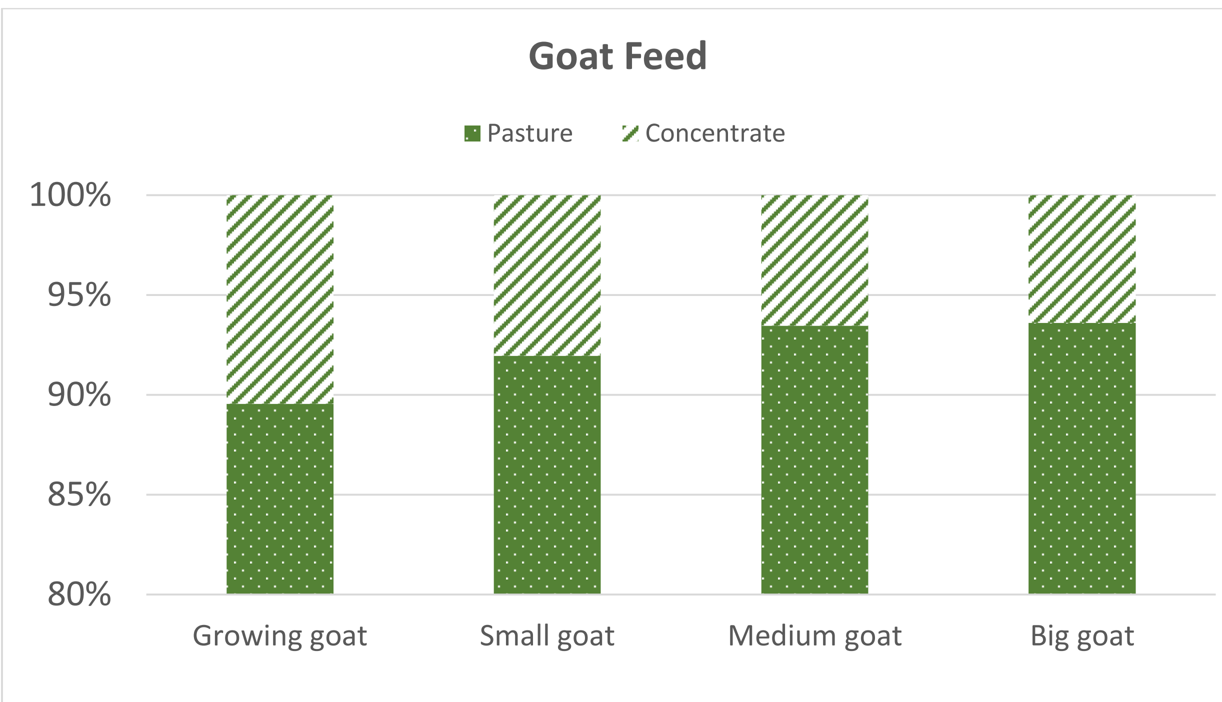


Figure 13: Goat feed composition as goat grows up *[88]*

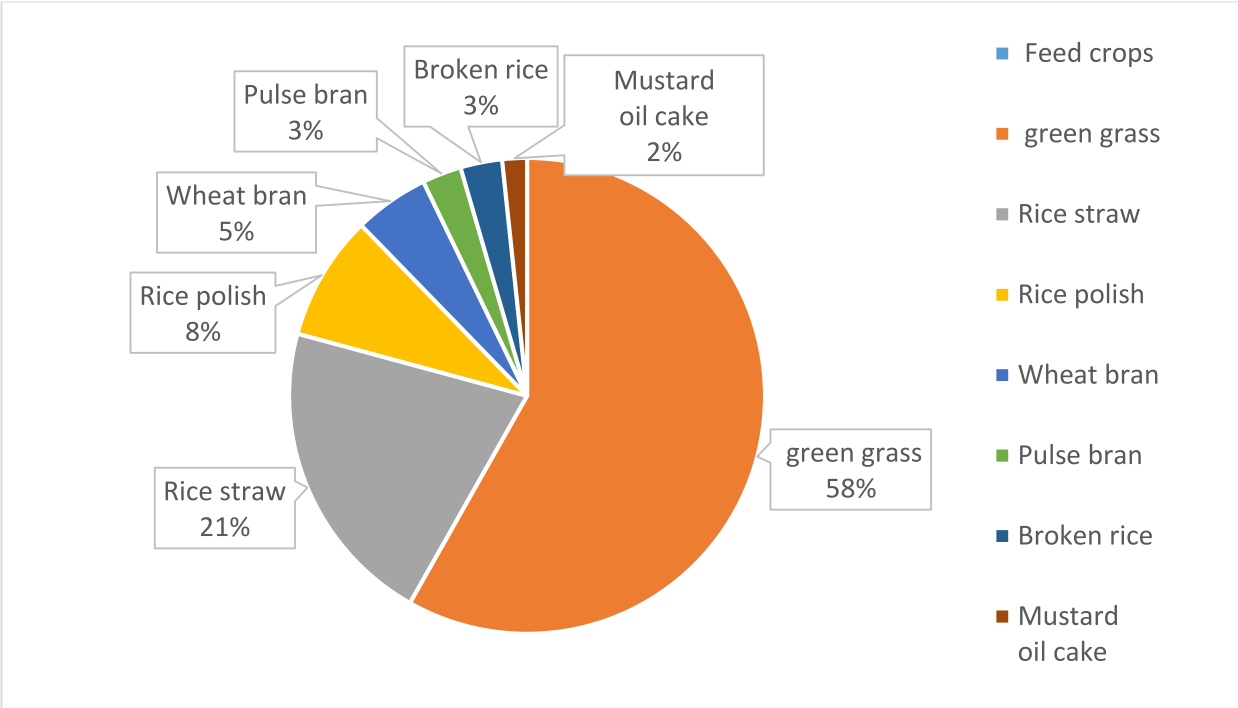


Figure 14: Cattle and buffalo seasonal feed composition in Bangladesh *[88]*

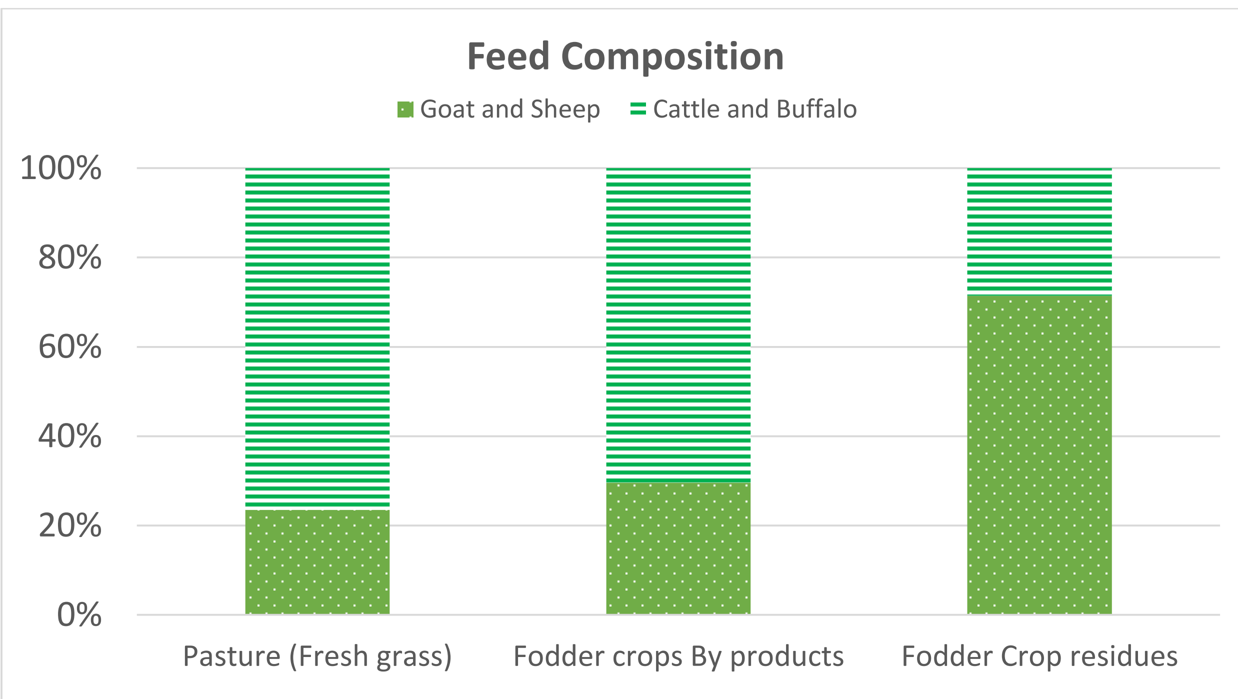


Figure 15: Feed composition comparison among livestock *[88]*

Table 13: Fibrous crop residue production *[76]*

Feed crops	**Types**	**Fresh ($\times 10^3$) (ton)**	**Dry matter ($\times 10^3$) (ton)**	**Availability ($\times 10^3$) (ton)**
Rice	Straw	44759	40283	20141
Maize	Stover	4084	2042	204.2
Wheat	Straw	1036	932	9.32
Minor cereals	Straw	3.8	3.49	
Pulses	Offal	928	835	835
Sugarcane	Tops	934	934	373
	Leaves	467	467	210
Potato	Plants	1665	1665	499
Mango, Pineapple, Banana, Jackfruit	Waste	630	630	93.83
Mulberry	Leaves	1.4	1.4	0.56
Vegetable	Waste	2629	2629	2.63
Pasture (Green Grass)		19272	19272	5781

Table 14: Cereal by-product production *[76]*

Feed crops	**Types**	**Production ($\times 10^3$) (ton)**	**Availability ($\times 10^3$) (ton)**
Rice	Bran	2754	2754
Maize	Corn	2042	2042
	Bran	163.4	163.4
Wheat	Wheat Bran	829	829
Minor Cereals			
Pulses	Bran	6.96	6.96
Sesame	oilcake	25.1	25.1
Rape and mustard	oilcake	18.2	18.2
Ground nut	oilcake	14.8	14.8
Coconut	oilcake	2.93	2.93
Cotton	oilcake	7.37	6.5
	Molasses	72	

3.2.3. Water Footprint of Tanneries

Tanneries water footprint only include blue water footprint and grey water footprint. As tanneries do not utilize the rain water, green water footprint has been excluded from the calculation. Both the blue water footprint and grey water footprint calculation method has been given below:

$$WF_{tannery} = WF_{blue,\ tannery} + WF_{grey,\ tannery} \quad (23)$$

3.2.3.1. Blue Water Footprint of Leather Process (Tannery):

The blue water footprint of tanneries has been calculated by water consumption in each stage of leather processing. In the production system, the water footprint of each product (e.g., Pelt, Wet blue leather, crust leather) WF[p] (m^3/kg) is equal to the sum of the relevant process water footprints divided by the production quantity of product *p*. In practice, simple production systems with only one output product rarely exist, thus a more generic way of calculation is necessary**.** So, in this study blue water footprint of tannery can be calculated as below:

$$WF_{blue,\ tannery} = \frac{\sum_{s=1}^{k} WF_{proc,blue}\,[s]}{P[p]} \quad (24)$$

in which $WF_{proc,\ blue}[s]$ is the process blue water footprint of process step *s* (m^3/year), and *P*[*p*] the production quantity of product *p* (ton/year). Process water footprint of each step is calculated by multiplying usage rate (UR%) (See table E1 from appendix E) of water in drums and annual production (AP) of leathers in equation 23.

$$WF_{proc,\ blue}\,[s] = (UR \times AP)/100 \quad (25)$$

3.2.3.2. Grey Water Footprint of Leather Process (Tannery):

The grey water footprint is also calculated by chain summation approach like blue water footprint. But here process grey water footprint is $WF_{proc,\ grey}$ [s].

$$WF_{grey,\ tannery} = \frac{\sum_{s=1}^{k} WF_{proc,grey}[s]}{P\,[p]} \quad (26)$$

The process grey water footprint, $WF_{proc, grey}$ [s] is calculated by dividing the pollutant load (L, in kg/year) by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration C_{max}, in kg/m^3) and its natural concentration in the receiving water body (C_{nat}, in kg/m^3).

$$WF_{proc, grey [s]} = \frac{L}{C_{max} - C_{nat}} \quad \ldots (27)$$

In the case that pollutants (e.g. BOD, COD) are part of an effluent discharged into a water body, the pollutant load can be calculated as the effluent volume ($Effl$, in m^3/year) multiplied by the difference between the concentration of the pollutant in the effluent (C_{effl}, in kg/m^3) minus the water volume of the abstraction (Abstr) multiplied by the actual concentration of the intake water (C_{act}). The actual and natural concentration of pollutants and ambient water quality standard for pollutants (e.g., BOD, COD) is given in Table 15.

$$WF_{proc, grey [s]} = \frac{Effl \times C_{eff} - Abst \times C_{act}}{C_{max} - C_{nat}} \quad \ldots (28)$$

Table 15: Pollutants concentration in groundwater, surface water and ambient water quality standard *[89] [51]*

Type of pollutants	Actual concentration in ground water, C_{act} (mg/l)	Natural concentration of surface water, C_{nat} (mg/l)	Ambient water quality standard, C_{max} (mg/l)
BOD	3	5	12
COD	10	15	200

Wastewater samples were collected from the outlet of the process of each stage of four tanneries. Each of these samples was tested multiple times in the Environmental Laboratory of Chemical Engineering Department, BUET. The average of the test results of concentration of the pollutant (BOD and COD) of four Tanneries effluents is presented in Table 16. In the calculation, BOD values of each stages and sub stages are considered for calculating grey water footprints of tanneries.

Table 16: Pollutants (e.g., BOD and COD) concentration in effluent from each stage of tanneries

Stages	Sub Stages	BOD (mg/l)	COD (mg/l)
Soaking	Pre soaking	2500	15900
	Main soaking	1810	9564
	Washing	1200	4667
Liming	Main Bath	2500	59698
	Washing	2200	4462
Chemical Wash	Washing	693	1184
Deliming and Bating	Washing	1980	10258
Pickling and Tanning	Main Bath	1816	6523
Wet back	Main Bath	855	2254
Rechroming	Washing	2367	24971
Neutralization	Main Bath	1440	5545
	Washing	772	2322
Retanning	Main Bath	1988	38482
Fatliquoring	Main Bath	3147	26034
Dyeing	Main Bath	2421	8208

3.2.4. Water Footprint of Workers

The water footprint of workers (WF_{worker}) is calculated by adding the direct water footprint of the individual workers in leather production. The direct water footprint refers to the water consumption and pollution that is related to water use at drums and machines in tanneries. Using equation 26, 27 and 28 water footprint of tannery workers is calculated. Also, it is similar to the calculation of the water footprint of tanneries (Section 3.1.3).

$$WF_{worker} = WF_{worker, blue} + WF_{worker, grey} \quad (29)$$

Blue Water Footprint of Workers:

$$WF_{worker, blue} = \frac{\sum_{s=1}^{k} WF_{worker,blue}\,[s]}{P\,[p]} \quad (30)$$

Grey Water Footprint of Workers:

$$WF_{worker, grey} = \frac{\sum_{s=1}^{k} WF_{worker,grey}\,[s]}{P\,[p]} \quad (31)$$

To calculate grey water footprint of workers there are certain data needed which are mentioned below. Survey has been conducted to collect the present data of tanneries.

Outlet water/person/day (m3)	=30
Outlet BOD (kg/m3)	=0.3
Number of working days (days)	=120
Number of tanneries	=155
Drums per operations	=2
Drums Capacity (kg)	=6000

More data were needed to calculate the water footprint of mechanical operations like fleshing, samming, splitting, shaving, vacuum drying etc. Survey has been conducted to collect the present data of tanneries and those data are collected from the tanners and leather technologist and given below.

Drum capacity (kg) for wet blue production	=6000
Drum capacity (pieces) for wet blue production	=234
Drum capacity (kg) for crust production	=800
Drum capacity (pieces) for crust production	=20
Weight of one raw hide (kg)	=25.6
Number of working days for post tanning	=120
Number of post tanning drums	=310
Number of workers per machine	=15
Washing Water per machine per day (m3)	=3
Weight of one shaved grain wet blue leather (kg)	=6.7
Weight of one shaved split wet blue leather (kg)	=2.2
Staking Machine, Toggling Machine, Buffing machine per tanneries	=1

3.2.4. Water Footprint of Chemicals

Different types of chemicals are used for the production of leather. Calculating water footprint of chemicals require assessment of the manufacturing process of each chemical. And water and chemicals are used in approx. 1000:1 ratio which makes the data less significant in the total water footprint of leather. So, because of the diverse data interpolation and high ratio of water in production the water footprint of chemicals is ignored in this study.

Chapter 4: Results and Discussion

4.1. Effluent Characteristics and Pollution Load of Tanneries

4.1.1. Characteristics of Effluent from Different Stages

Each stage of the leather processing produces effluents which are different in characteristics. In table 16 each stage and their sub stages effluent characteristics are given. BOD, COD, TDS and TSS values are average of four tanneries. Soaking and liming stage has high BOD, COD, TDS and TSS. Effluent from liming has high pH as this stage is alkaline in nature. Tanning and rechroming effluent has low pH as this stage processing is acidic. Effluents from each stage has got high pollutants concentration as the effluent contains heavy and non-biodegradable solids. Particularly, liming main bath effluent has BOD 2500 mg/l, COD 60000 mg/l, TDS 14720 mg/l and TSS 51400 mg/l which are highest value.

Table 17: Stagewise pollutants (e.g., pH, BOD, COD, TDS and TSS) concentration of tannery effluent

Stages	Sub stages	pH	BOD (mg/l)	COD (mg/l)	TDS (mg/l)	TSS (mg/l)
Soaking	Pre soaking	6.99	2500	15900	4440	1240
	Main soaking	9.82	1810	9564	17078	11109
	Washing	7.34	1200	4667	17078	14700
Liming	Main Bath	11.94	2500	59698	14720	51369
	Washing	12.93	2200	4462	5210	3670
Chemical Wash	Washing	9.16	693	1184	2230	1240
Deliming and Bating	Washing	8.07	1980	10258	20250	27942
Pickling and Tanning	Main Bath	3.47	1816	6523	24148	45488
Wet back	Main Bath	2.19	855	2254	6954	6181
Rechroming	Washing	3.85	2367	24971	7493	11431
Neutralization	Main Bath	4.69	1440	5545	9085	12017
	Washing	5.03	772	2322	4030	2895
Retanning	Main Bath	5.50	1988	38482	10053	21651
Fatliquoring	Main Bath	4.98	3147	26034	7493	19477
Dyeing	Main Bath	4.47	2421	8208	5057	9039

Direct discharge effluent from tanneries does not fulfill the effluent quality standards but quality of effluent after treatment from CETP is close to the standards. In table 18 value of parameters of tannery effluent and CETP final discharge effluent are given.

Table 18: Comparison of tannery effluent quality experimental data and quality standards

Parameter	Effluent quality standard ECR 97, schedule 12(I) (mg/l)	Tannery effluent quality (mg/l)
pH	6-9	5.81
BOD	100	2412
COD	----	5442
TDS	2100	4840
TSS	150	843

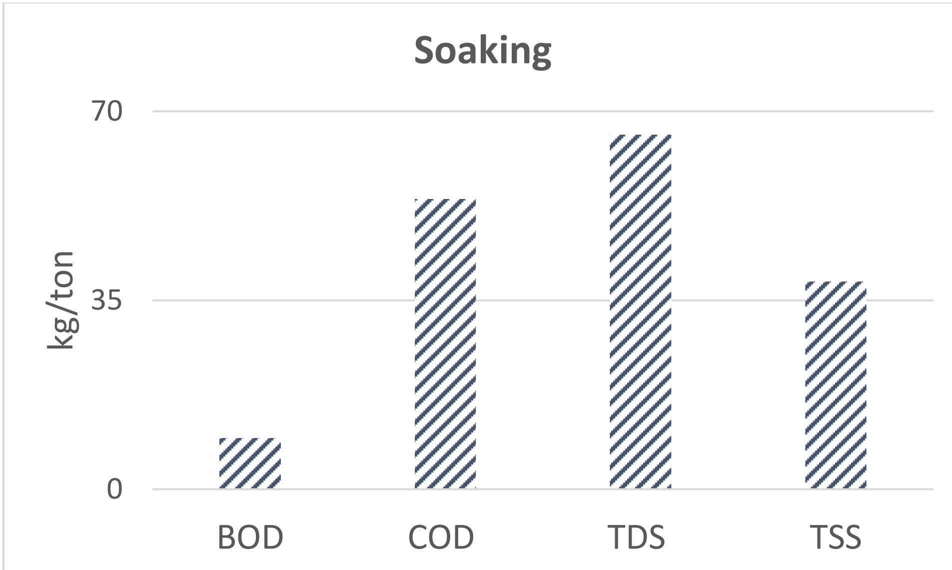
4.1.2. Yearly Pollution Load of Each Stage of Tanneries

Pollution load of each stage of leather processing has found to be very high each year. Almost 2.65 million effluent generates from soaking and liming stage (See Table C1). All the stage generates large number of pollutants each year. From FY 2013 to FY 2017 the pollution loads (e.g. BOD, COD, TDS and TSS) are mentioned in the tables given in appendix C [See Table C1-C5].

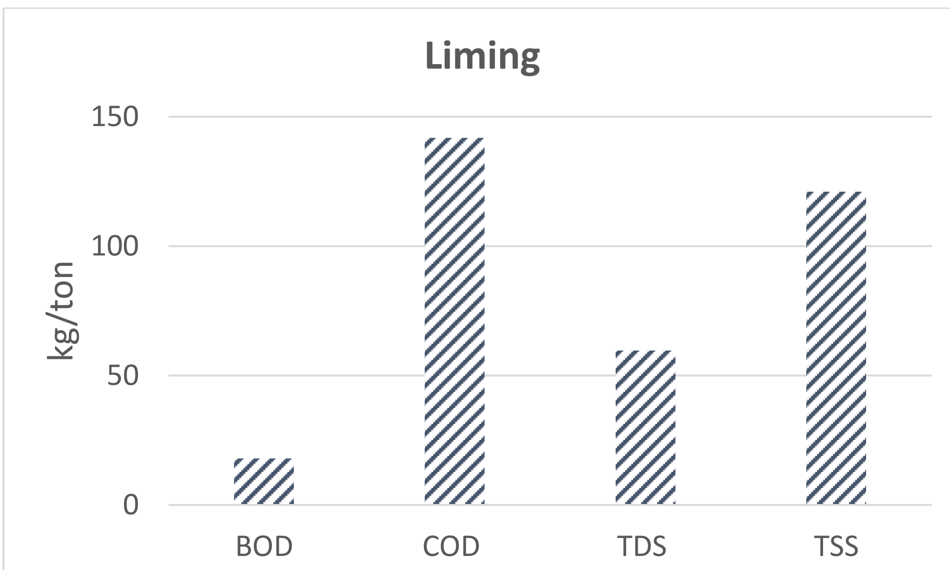
4.1.3. Stagewise Pollution Load of Tanneries

Beam House Operations

Soaking includes presoaking, main soaking and washing stages. It has BOD 10 kg/ton, COD 54 kg/ton, TDS 66 kg/ton and TSS 39 kg/ton. Pollution load of soaking stage is given in figure 16a. Soaking effluent is second most polluted after liming. It contains high amount of salt for salt curing of hides and skins in Bangladesh. Liming stage has BOD 18 kg/ton, COD 142 kg/ton, TDS 60 kg/ton and TSS 121 kg/ton. Pollution load of Liming stage is given in figure 16b. This stage produces maximum number of pollutants. Liming generates the most polluted effluent and it contains lime and dirt. Its TSS is almost 120 kg/ton it means effluent contains many solids like hair, blood, flesh residue.



(a)

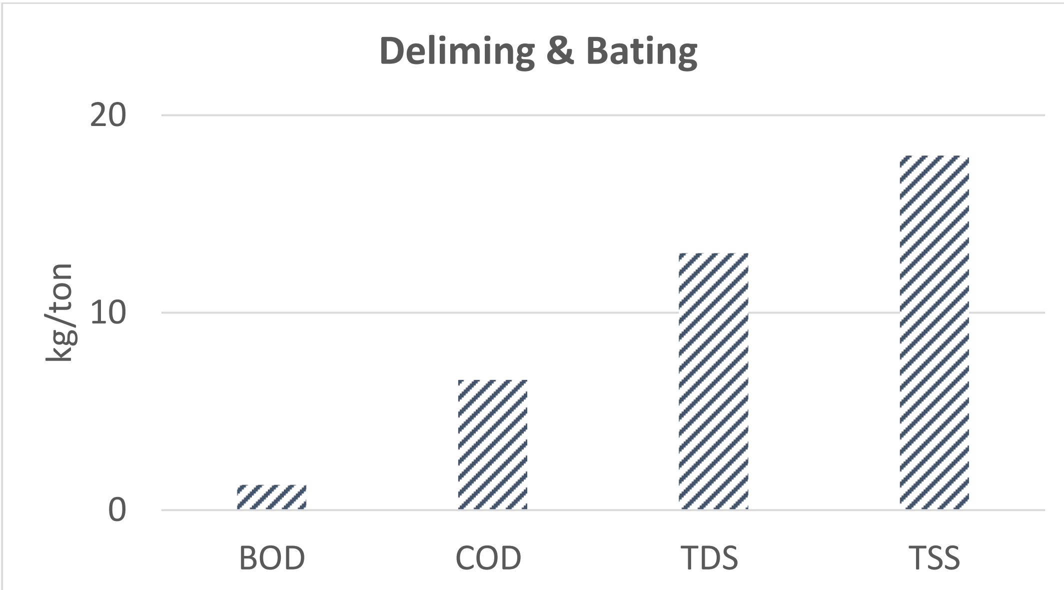


(b)

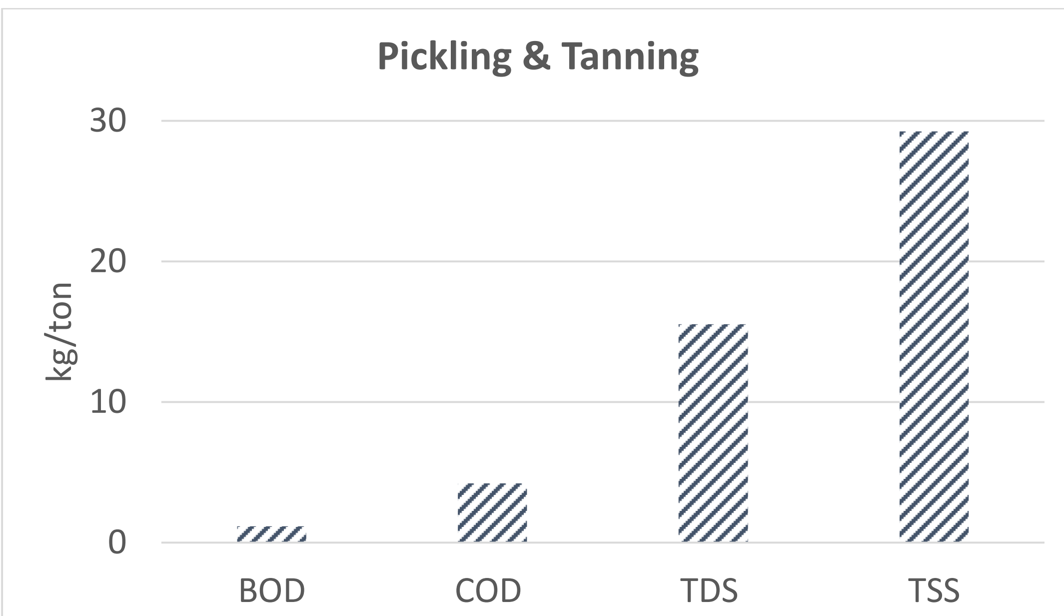
Figure 16: Pollution load of (a) soaking (b) liming stage of beam house operations in leather production

Tan Yard Operations

Deliming and Bating stage has BOD 1 kg/ton, COD 7 kg/ton, TDS 13 kg/ton and TSS 18 kg/ton. Pollution load of Deliming and Bating stage is given in figure 17a. Delime washing effluent has low BOD and COD but high TSS still less than liming and soaking effluent. Pickling and Tanning stage has BOD 1 kg/ton, COD 4 kg/ton, TDS 16 kg/ton and TSS 29 kg/ton. Pollution load of Pickling and Tanning stage is given in figure 17b.



(a)



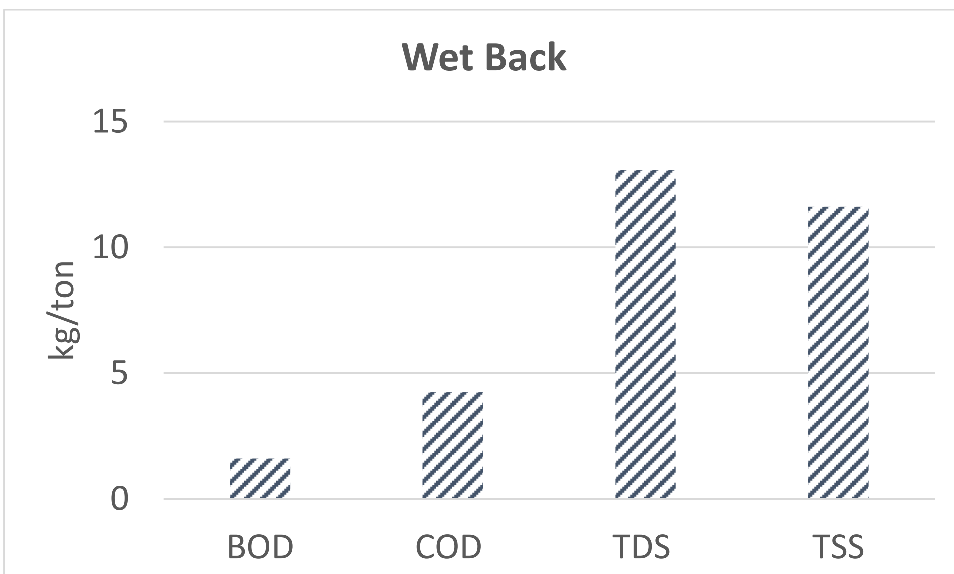
(b)

Figure 17: Pollution load of (a) deliming and bating, (b) pickling and tanning stage of tan yard operations in leather production

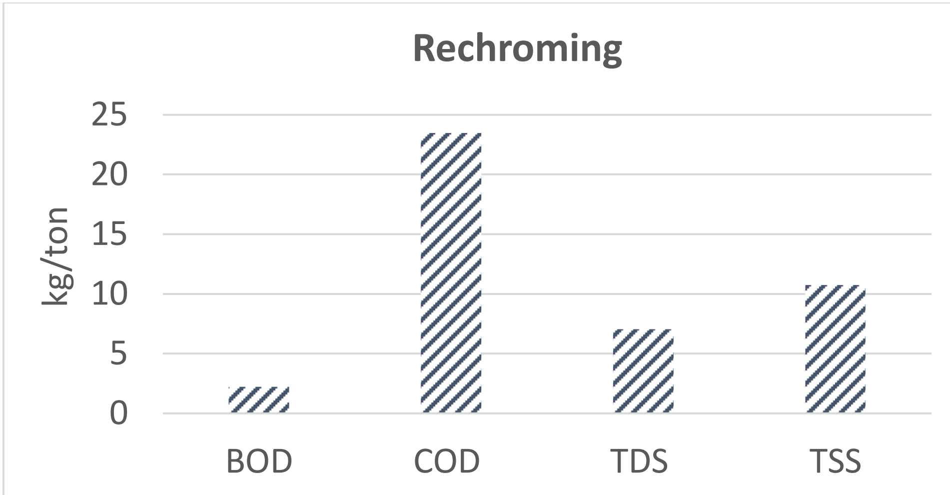
Post Tanning Operations

Wet back stage has BOD 2 kg/ton, COD 4 kg/ton, TDS 13 kg/ton and TSS 12 kg/ton. Pollution load of Wet back stage is given in figure 18a. Rechroming stage has BOD 2 kg/ton, COD 23 kg/ton, TDS 7 kg/ton and TSS 11 kg/ton. Pollution load of Rechroming stage is given in figure 18b. Neutralization stage has BOD 3 kg/ton, COD 11 kg/ton, TDS 26 kg/ton and TSS 55 kg/ton. Pollution load of Neutralization stage is given in figure 18c.

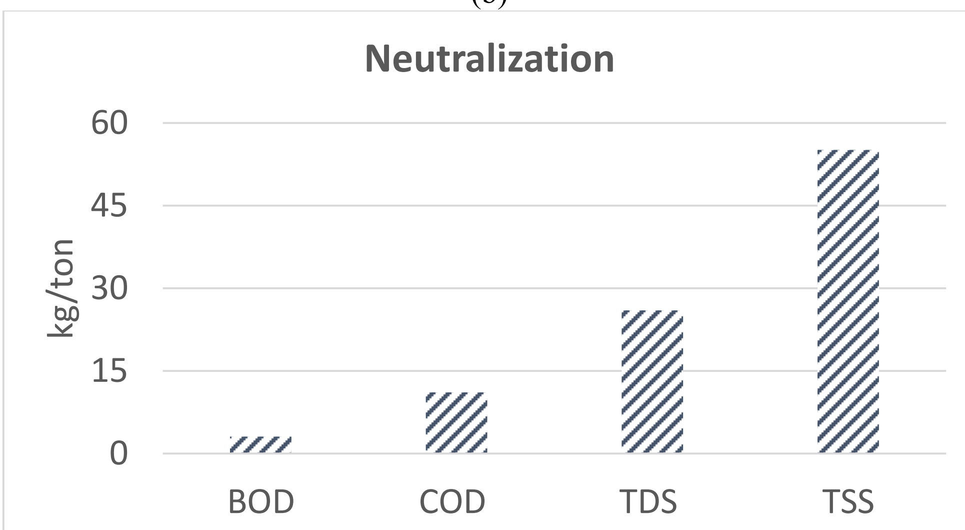
Retanning stage has BOD 3 kg/ton, COD 54 kg/ton, TDS 14 kg/ton and TSS 31 kg/ton. Pollution load of Retanning stage is given in figure 18d. Dyeing stage has BOD 2 kg/ton, COD 5 kg/ton, TDS 3 kg/ton and TSS 6 kg/ton. Pollution load of Dyeing stage is given in figure 18e. Fatliqouring stage has BOD 3 kg/ton, COD 25 kg/ton, TDS 7 kg/ton and TSS 19 kg/ton. Pollution load of Fatliqouring stage is given in figure 18f.



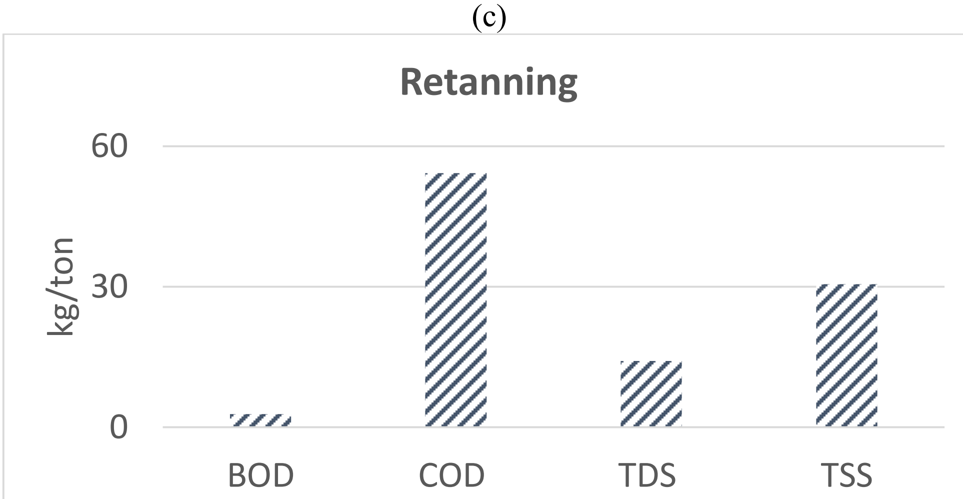
(a)


Rechroming
25
20
15
10
5
0
kg/ton
BOD
COD
TDS
TSS

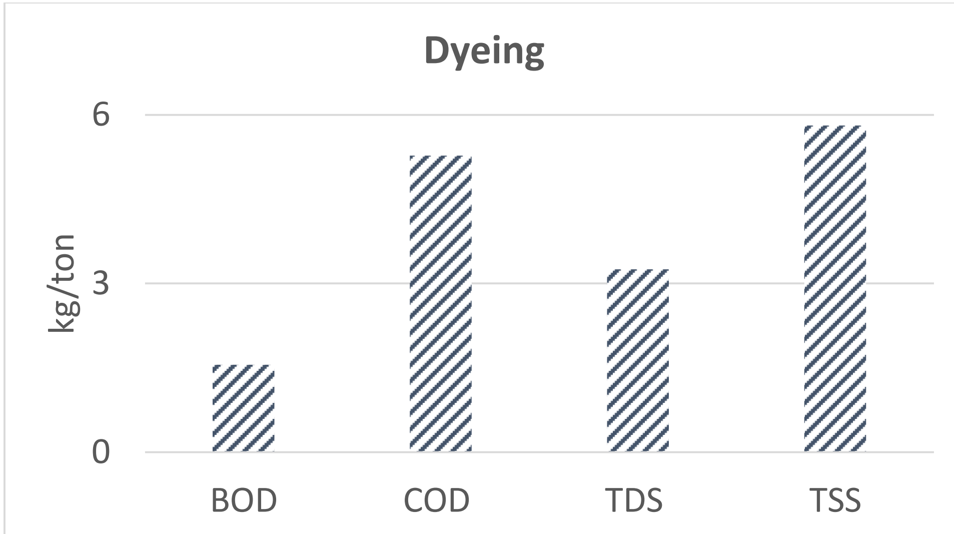
(b)


Neutralization
60
45
30
15
0
kg/ton
BOD
COD
TDS
TSS

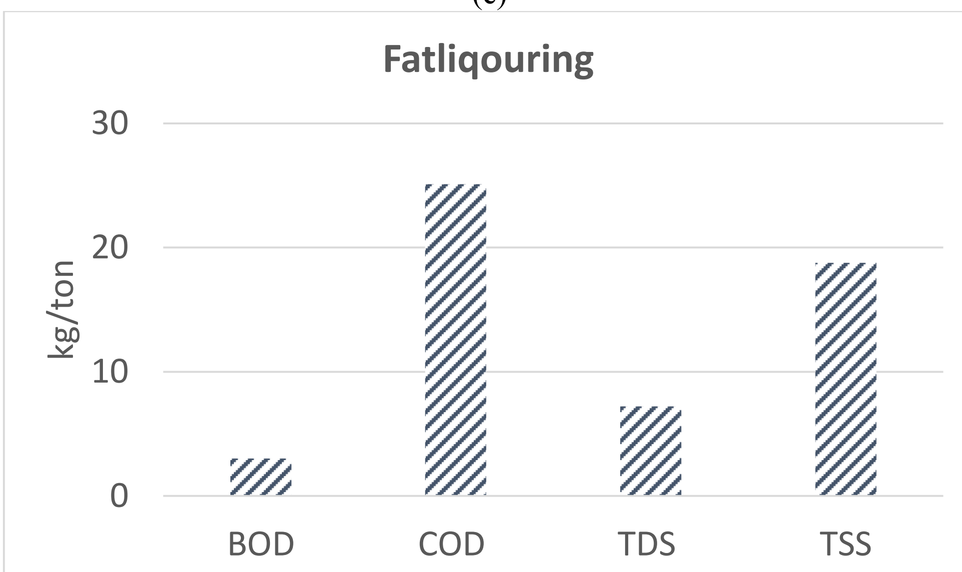
(c)


Retanning
60
30
0
kg/ton
BOD
COD
TDS
TSS

(d)



(e)



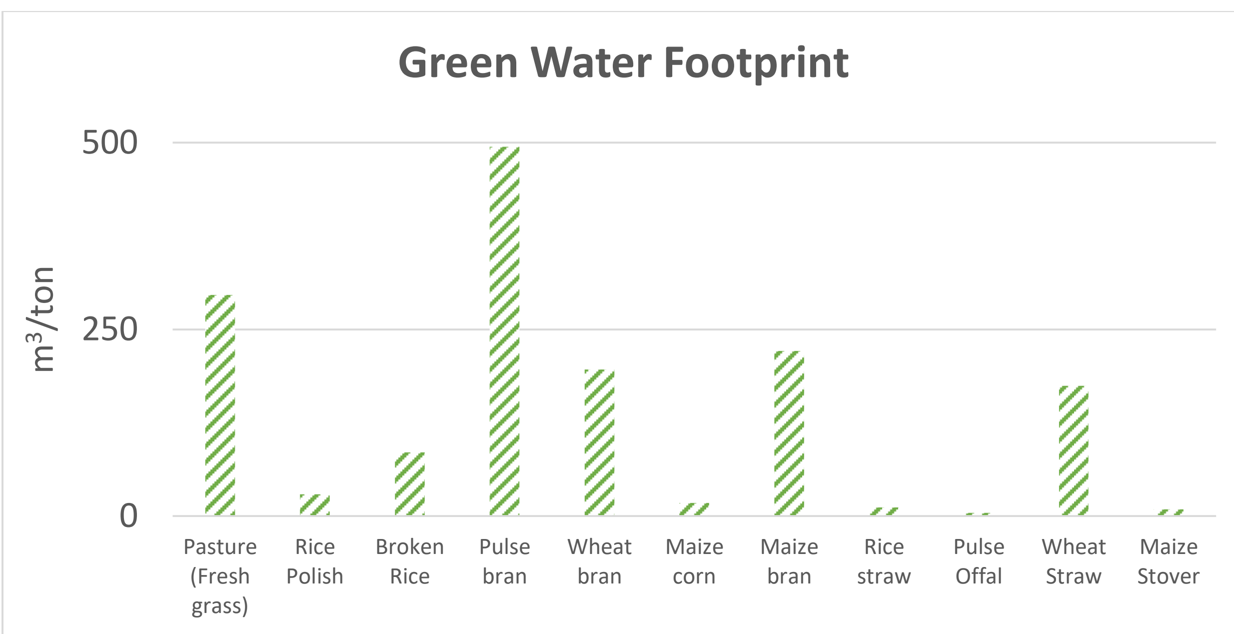
(f)

Figure 18: Pollution load of post tanning operations (a) wet back, (b) rechroming (c) neutralization, (d) retanning (e) dyeing (f) fatliqouring in leather production

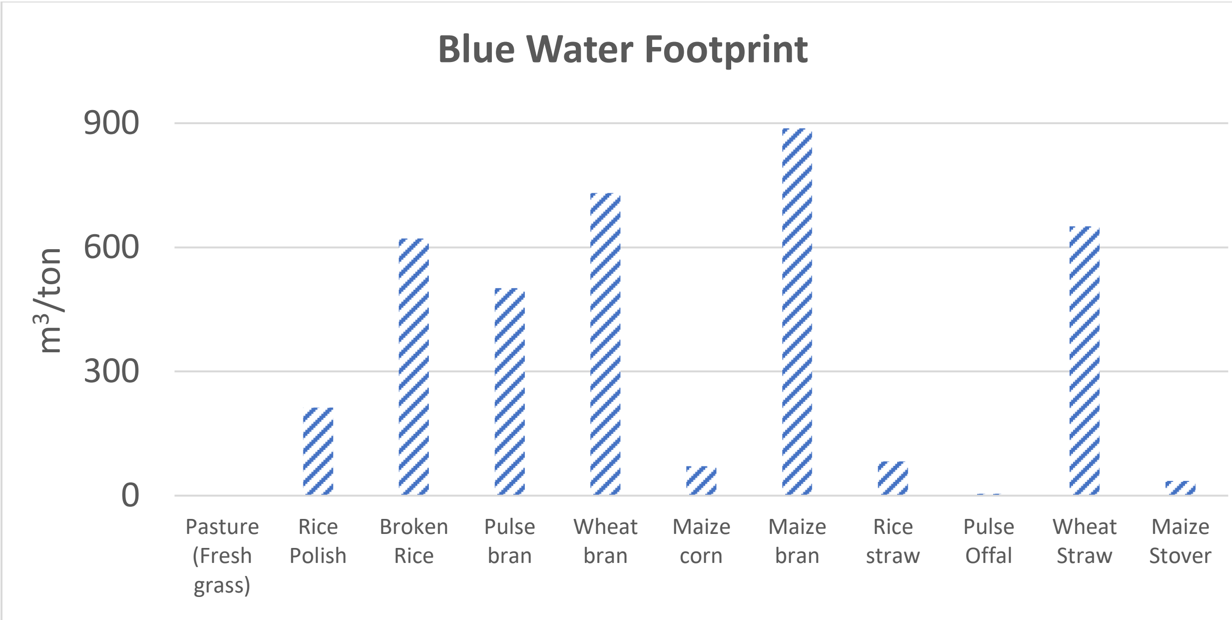
4.2. Water Footprint of Feed crops and Raw Hides

4.2.1. Water Footprint of Feed crops

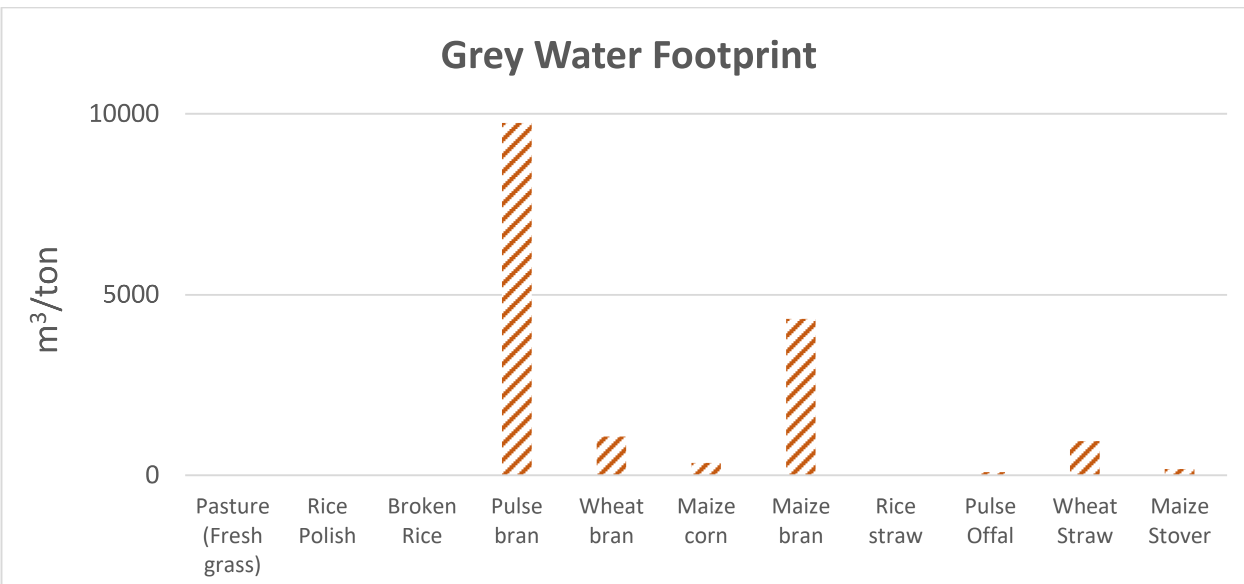
In figure 19 pasture, the main feed crop of bovine and ovine in Bangladesh has the green water footprint 296 m^3/ton. Pasture does not have any blue and grey water footprint as in Bangladesh grassland mainly depends on rain water. Rice straw is another main feed crop for cattle and buffaloes in Bangladesh. As rice is main food in Bangladesh rice is easily available. Rice straw has green water footprint 11.32 m^3/ton, blue water footprint 82.67 m^3/ton and grey water footprint 0.43 m^3/ton (See figure 19). Rice polish is a byproduct of rice obtained in the milling operations. It is also important feed ingredient for cattle and buffaloes in Bangladesh. Rice polish has the green water footprint 29.11 m^3/ton, Blue water footprint 212.62 m^3/ton and grey water footprint 11.02 m^3/ton. It has low green and grey water footprint. Broken rice is the fragment of rice grain. It is also an important feed ingredient. It has green water footprint 85.05 m^3/ton, blue water footprint 621 m^3/ton and very negligible grey water footprint. It has high blue water footprint explains its surface water consumption during rice cultivation. Wheat Straw is the hard-outer layer of wheat kernel which is jam-packed with various nutrients and fibers so it also very popular feed ingredient for beef cattle in Bangladesh. It has green water footprint 174 m^3/ton, blue water footprint 650 m^3/ton and grey water footprint 947 m^3/ton (See figure 19).



(a)



(b)



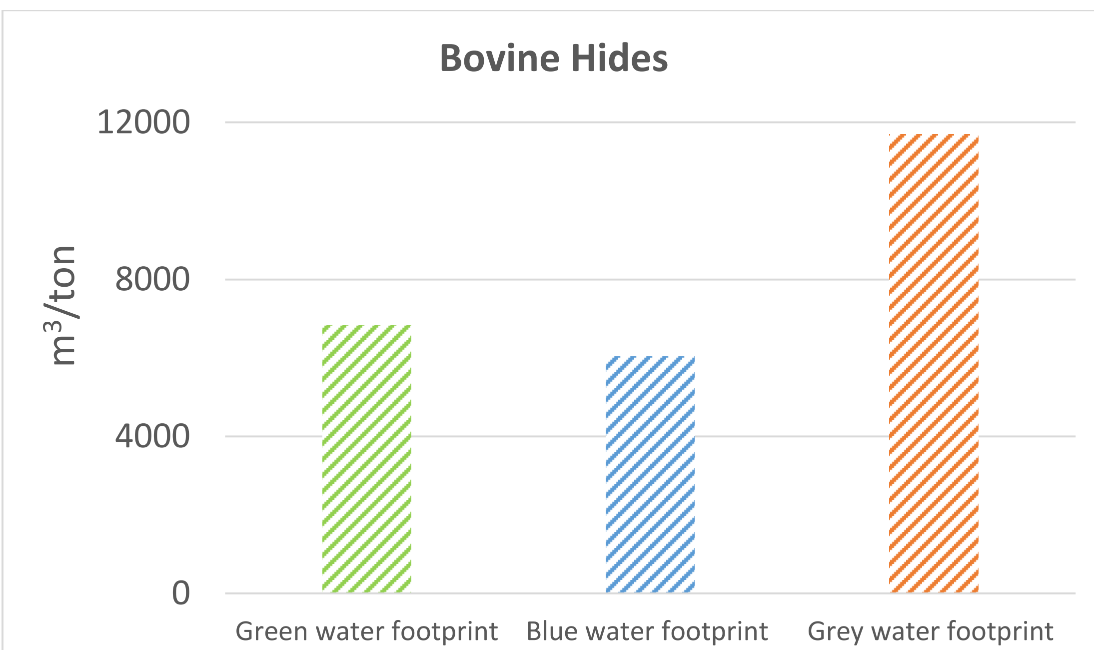
(c)

Figure 19: Water footprint of feed crops for farming animals in Bangladesh (a) Green water footprint (b) Blue water footprint (c) Grey water footprint

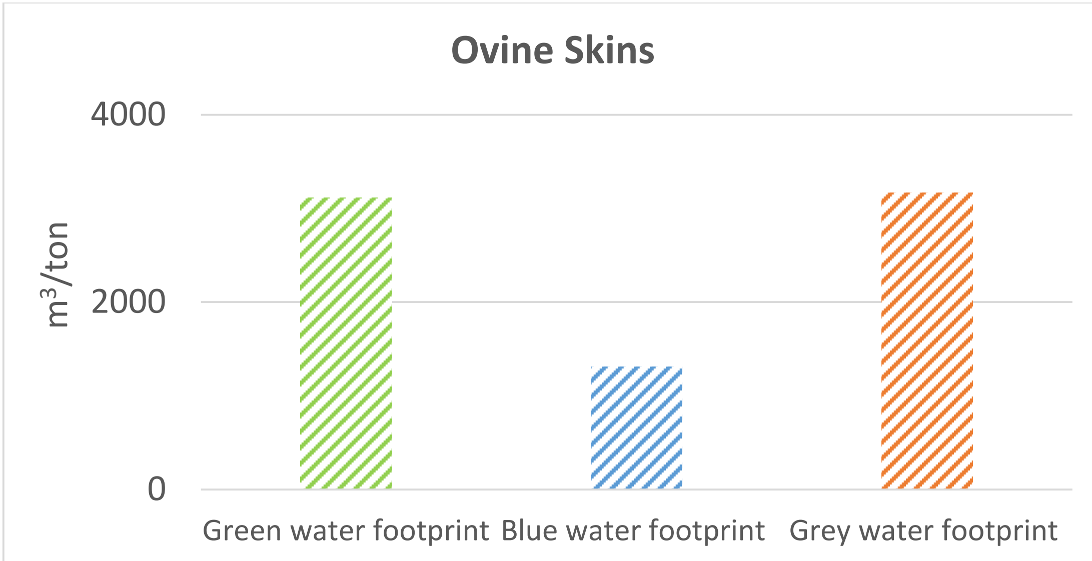
Wheat Bran has green water footprint 196 m^3/ton, blue water footprint 731 m^3/ton and grey water footprint 1065 m^3/ton. Grey Water footprint is very high for wheat cultivation method used in Bangladesh. Maize Corn is important feed crop for cattle as it adds nutritional value for farming animals. It has green water footprint 17.7 m^3/ton, blue water footprint 71 m^3/ton and grey water footprint 346 m^3/ton. Maize Bran has green water footprint 221 m^3/ton, blue water footprint 887 m^3/ton and grey water footprint 4330 m^3/ton. It has again higher grey water footprint and it is probably higher than rice polish (bran) and wheat bran. Maize Stover has green water footprint 8.85 m^3/ton, blue water footprint 35.5 m^3/ton and grey water footprint 173 m^3/ton. Pulse Bran has green water footprint 494 m^3/ton, blue water footprint 501 m^3/ton and grey water footprint 9748 m^3/ton. Pulse bran has the highest grey water footprint compared with rice residue, wheat bran, maize bran or other by products. Pulse Offal has green water footprint 4.12 m^3/ton, blue water footprint 4.18 m^3/ton and grey water footprint 81.26 m^3/ton (See figure 19).

4.2.2. Water Footprint of Bovine Hides and Skins

Bovine Hide is most common in Bangladesh local market. It has green water footprint 6840 m^3/ton, blue water footprint 6031 m^3/ton and grey water footprint 11689 m^3/ton (See figure 20a). It also means per kg hide green water footprint 6840L, blue water footprint 6031L, and grey water footprint 11689L and total water footprint 24560L. Ovine skin includes both goatskin, sheepskin and lambskin in Bangladesh but goat skin is mostly available. It has green water footprint 3113 m^3/ton, blue water footprint 1308 m^3/ton and grey water footprint 3167 m^3/ton (See figure 20b).



(a)



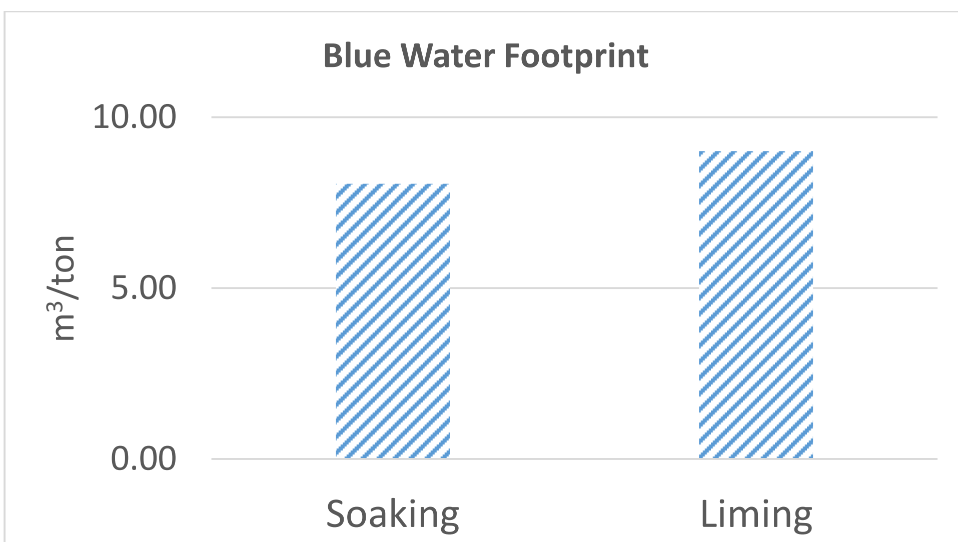
(b)

Figure 20: Water footprint (green, blue, grey) of (a) Bovine hide and (b) Ovine skin

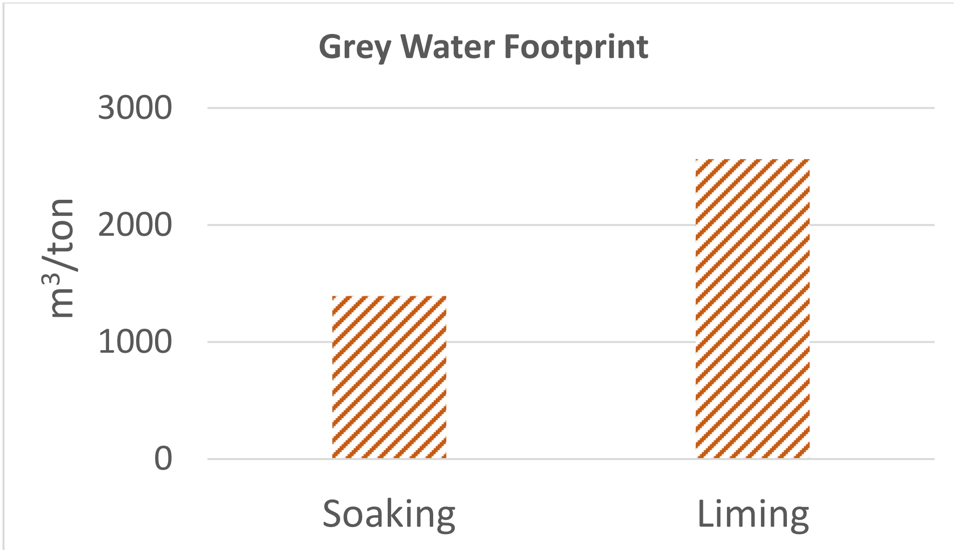
4.3. Water Footprint of Tanneries

4.3.1. Water Footprint of Beam House Operations

In beam house operations of leather production soaking and liming stage has 8.05 and 9.00 m^3/ton blue water footprint (See figure 21a) and 1394 and 2563 m^3/ton grey water footprint (See figure 21b). Here grey Water footprint is much higher than blue water footprint.



(a)

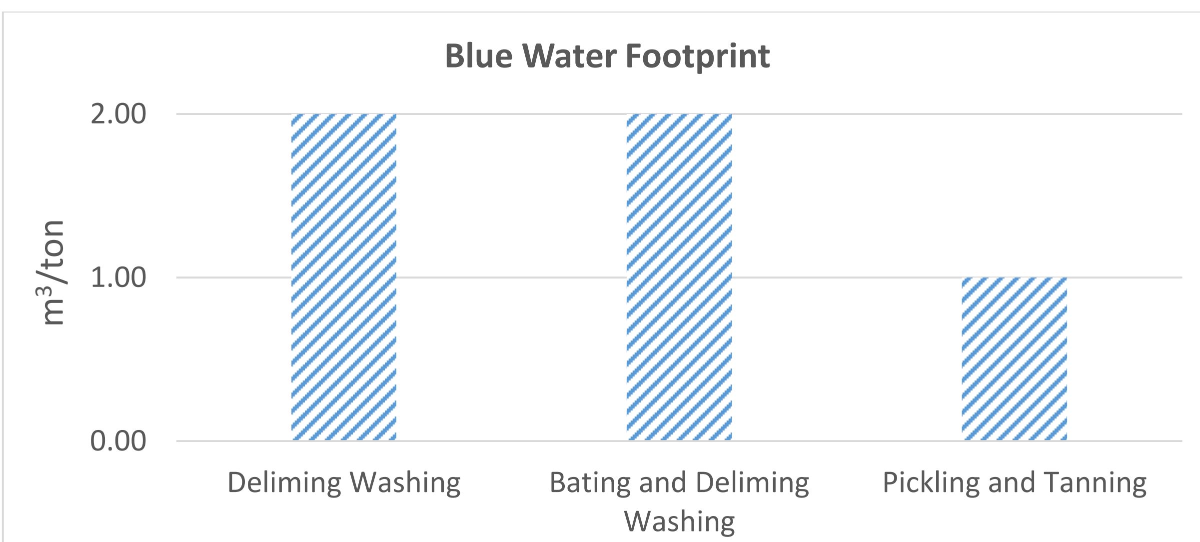


(b)

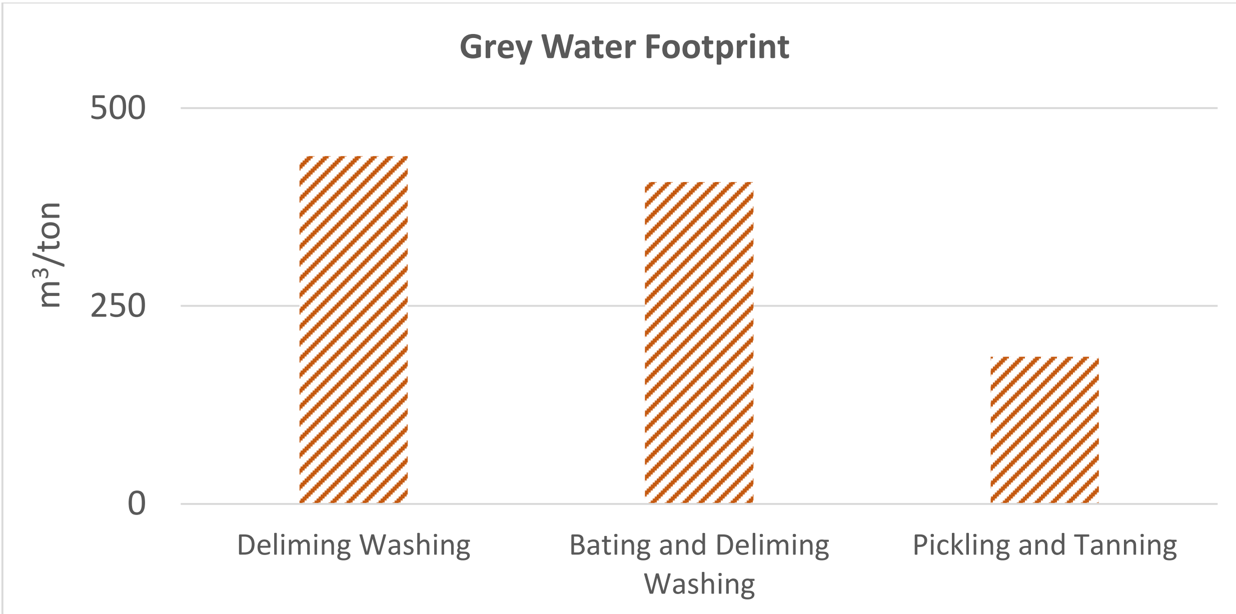
Figure 21: Water footprint of beam house operations (a) Blue water footprint (b) Grey water footprint

4.3.2. Water Footprint of Tan Yard Operations

In Tan yard Operations Deliming wash, Bating and deliming, pickling and tanning stages have 2, 2 and 1 m^3/ton blue water footprint (See figure 22a) and 439, 407 and 186 m^3/ton grey water footprint (See figure 22b).



(a)

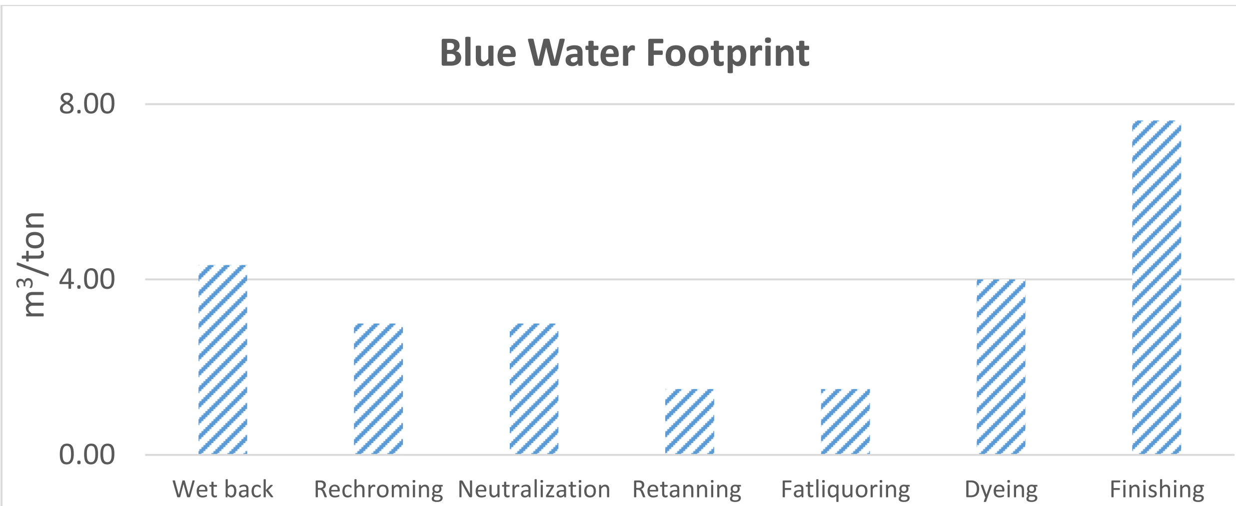


(b)

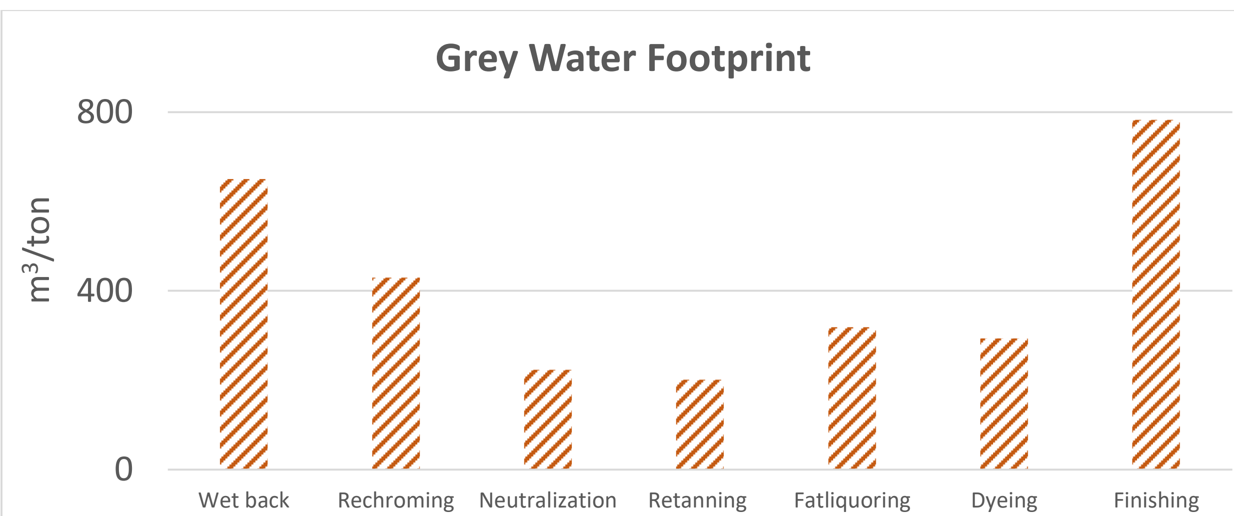
Figure 22: Water footprint of tan yard operations (a) Blue water footprint, (b) Grey water footprint

4.3.3. Water Footprint of Post Tanning Operations

In Post Tanning Operations Wet back has 4.33 m^3/ton, Rechroming has 3.00 m^3/ton, Neutralization 3.00 m^3/ton, Retanning has 1.50 m^3/ton, Fatliqouring has 1.5 m^3/ton, dyeing has 4.00 m^3/ton and finishing has 7.63 m^3/ton blue water footprint (See figure 23a) Wet back has 650 m^3/ton, Rechroming has 430 m^3/ton, Neutralization 223 m^3/ton, Retanning has 201 m^3/ton, Fatliqouring has 319 m^3/ton, dyeing has 294 m^3/ton and finishing has 783 m^3/ton grey water footprint (See figure 23b)



(a)

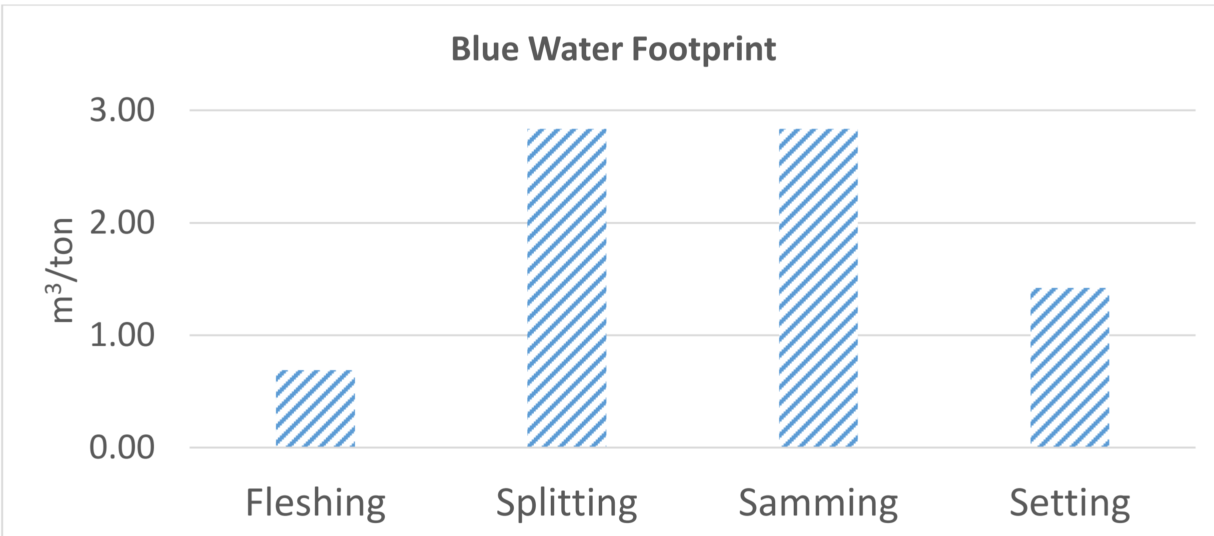


(b)

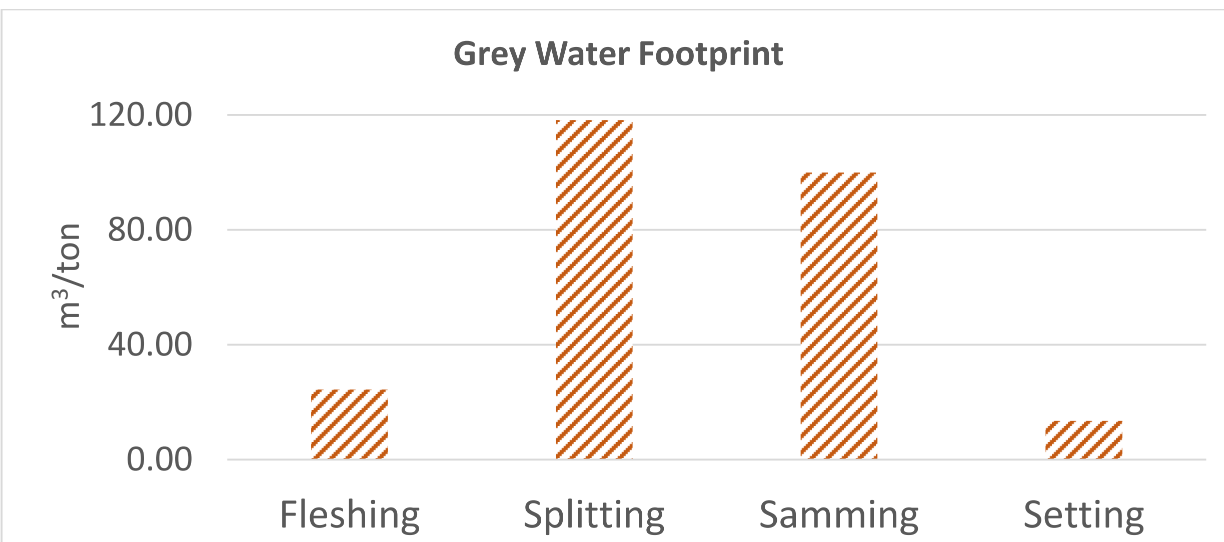
Figure 23: Water footprint of post tanning operations (a) Blue water footprint (b) Grey water footprint

4.3.4. Water Footprint of Mechanical Operations

Leather production has many mechanical operations in which water involves in fleshing, splitting, samming and setting machines. So, fleshing, splitting, samming and setting machines has 0.69, 2.84, 2.84 and 1.42 m^3/ton blue water footprint and grey water footprint 24.34, 118, 99.98 and 13.42 m^3/ton (See figure 24a, 24b).



(a)



(b)

Figure 24: Water footprint of mechanical operations (a) Blue water footprint (b) Grey water footprint

4.4. Water Footprint of Products

4.4.1. Water Footprint of Wet Blue Leather

Wet blue leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6062 m^3/ton and grey water footprint 17770 m^3/ton. Wet blue leather from ovine hides has green water footprint 3113 m^3/ton, blue water footprint 1373 m^3/ton and grey water footprint 9149 m^3/ton (See figure 25).

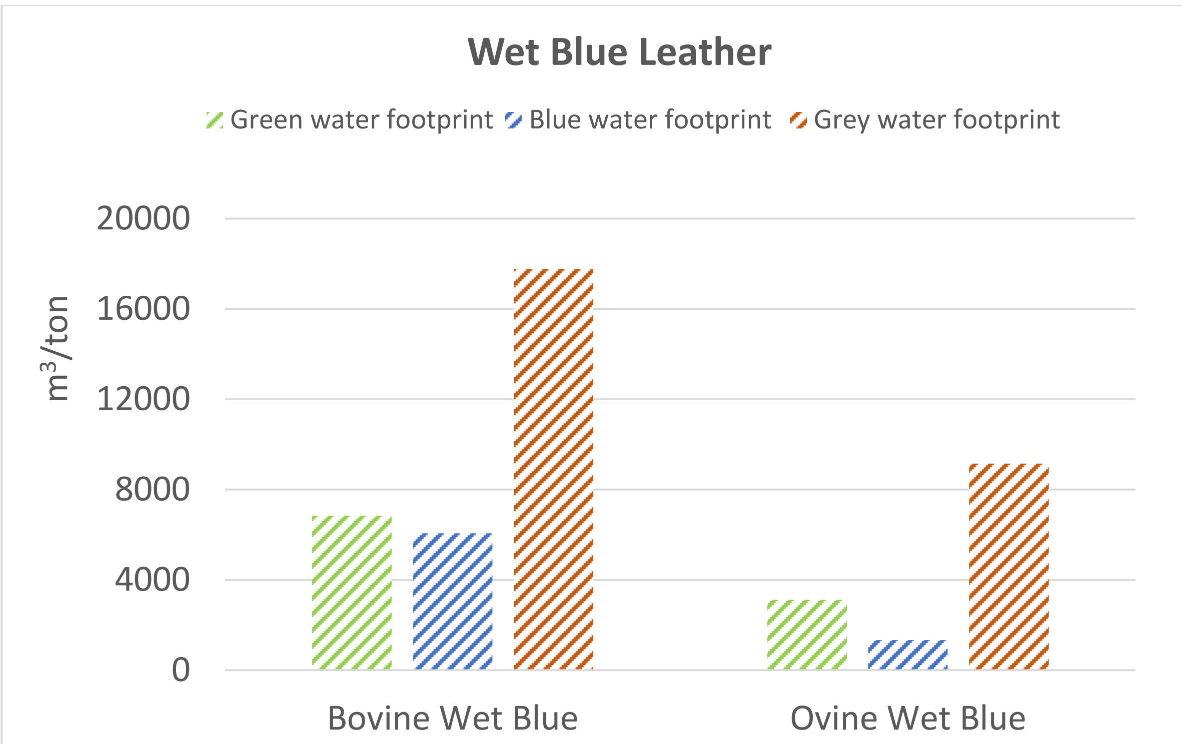


Figure 25: Water footprint (green, blue, grey) of wet blue leather

4.4.2. Water Footprint of Crust Leather

Crust leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6088 m^3/ton and grey water footprint 21121 m^3/ton. Crust leather from ovine hides has green water footprint 3113 m^3/ton, blue water footprint 1373 m^3/ton and grey water footprint 12885 m^3/ton (See figure 26).

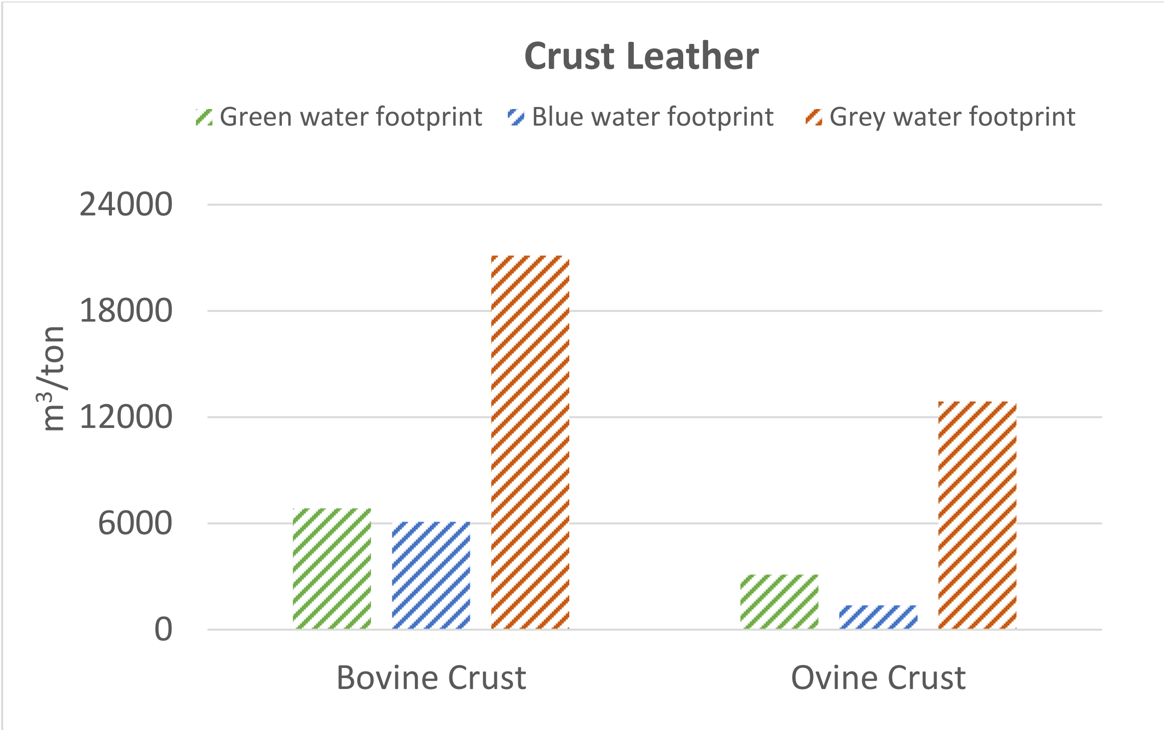


Figure 26: Water footprint (green, blue, grey) of crust leather

4.4.3. Water Footprint of Finished Leather and Others

Finished leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6096 m^3/ton and grey water footprint 21904 m^3/ton. Full grain leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6088 m^3/ton and grey water footprint 21121 m^3/ton. Top grain leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6062 m^3/ton and grey water footprint 17771 m^3/ton. Corrected leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6106 m^3/ton and grey water footprint 21971 m^3/ton. Split leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6062 m^3/ton and grey water footprint 17771 m^3/ton. Suede leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6088 m^3/ton and grey water footprint 21121 m^3/ton. Nappa leather from bovine hides has green water footprint 6840 m^3/ton, blue water footprint 6106 m^3/ton and grey water footprint 21971 m^3/ton (See figure 27).

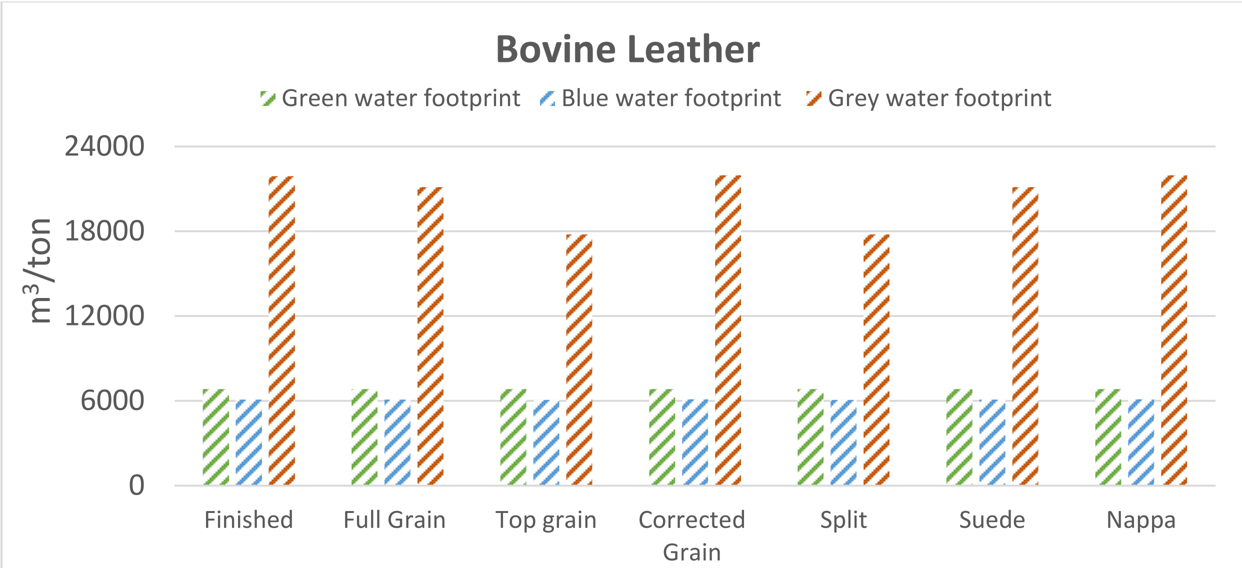


Figure 27: Water footprint (green, blue, grey) of bovine finished leather

Finished Full grain leather from ovine skins has green water footprint 3113 m^3/ton, blue water footprint 1381 m^3/ton and grey water footprint 13668 m^3/ton (See figure 36). Corrected leather from ovine hides has green water footprint 3113 m^3/ton, blue water footprint 1391 m^3/ton and grey water footprint 13735 m^3/ton. Suede leather from ovine hides has green water footprint 3113 m^3/ton, blue water footprint 1373 m^3/ton and grey water footprint 12885 m^3/ton. Nappa leather from ovine hides green water footprint 3113 m^3/ton, blue water footprint 1391 m^3/ton and grey water footprint 13735 m^3/ton (See figure 28).

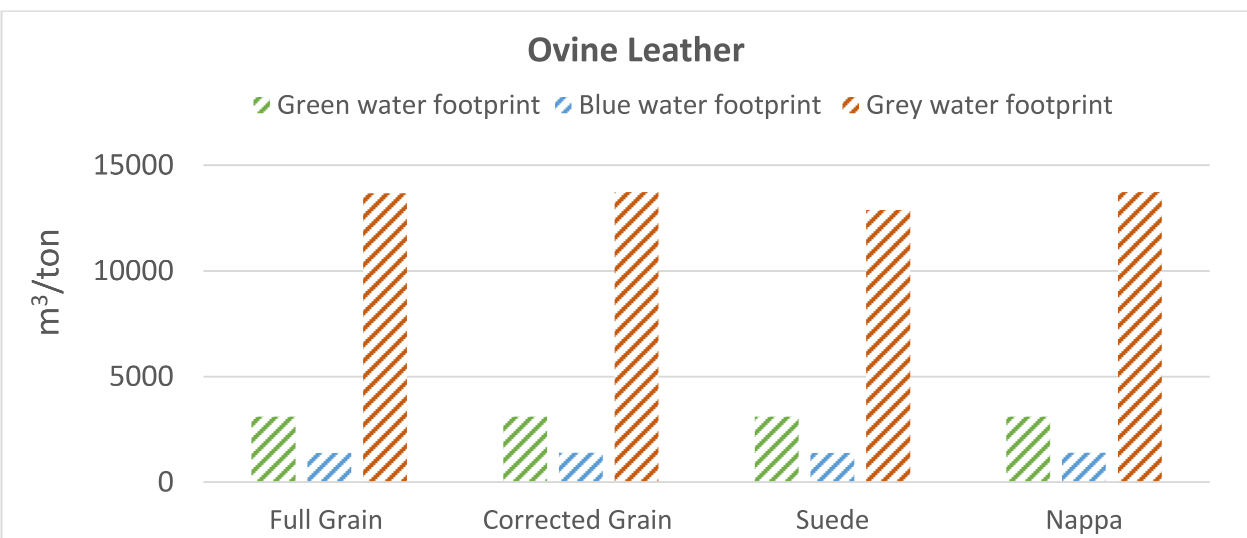


Figure 28: Water footprint (green, blue, grey) of ovine finished leather

Chapter 5: Impact Assessment

This chapter has been organized with impact assessments of tanneries on environment. It contains two section 5.1 and 5.2 in which water footprint assessment and pollution load assessment for tanneries will be discussed.

5.1. Water Footprint Assessment

As leather is processed from the by product (raw hide and skin) of the meat processing sector, it has long supply chain from farming section to final product. Determining water footprint of feed crop, then water footprint of hides and skins of farm animals then water footprint of leather has been calculated.

5.1.1. Contribution of Farming Sector in Water Footprint of Leather:

Bangladesh has large population of cattle, buffalo, goat and sheep. So, Hides and skins are collected from local markets. So, the water footprint of hides and skins of farming animals are considered to be domestic water footprint of Bangladesh as their feed crops are internal in the country. In Appendix D the green, blue and grey water footprint of feed crops are given in tabular form.

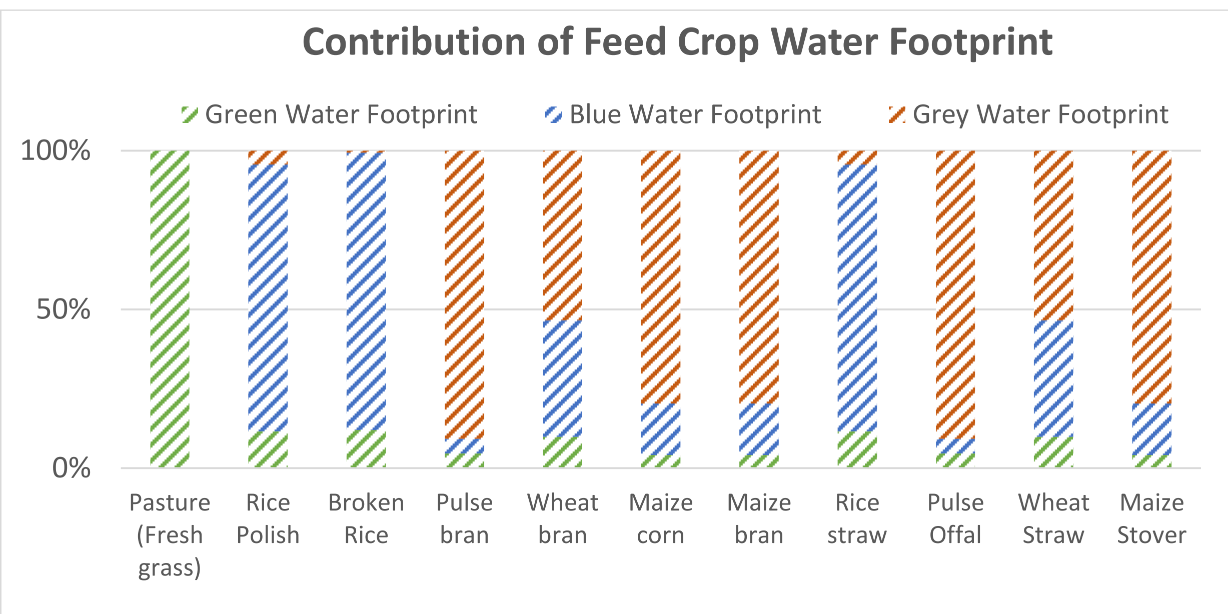
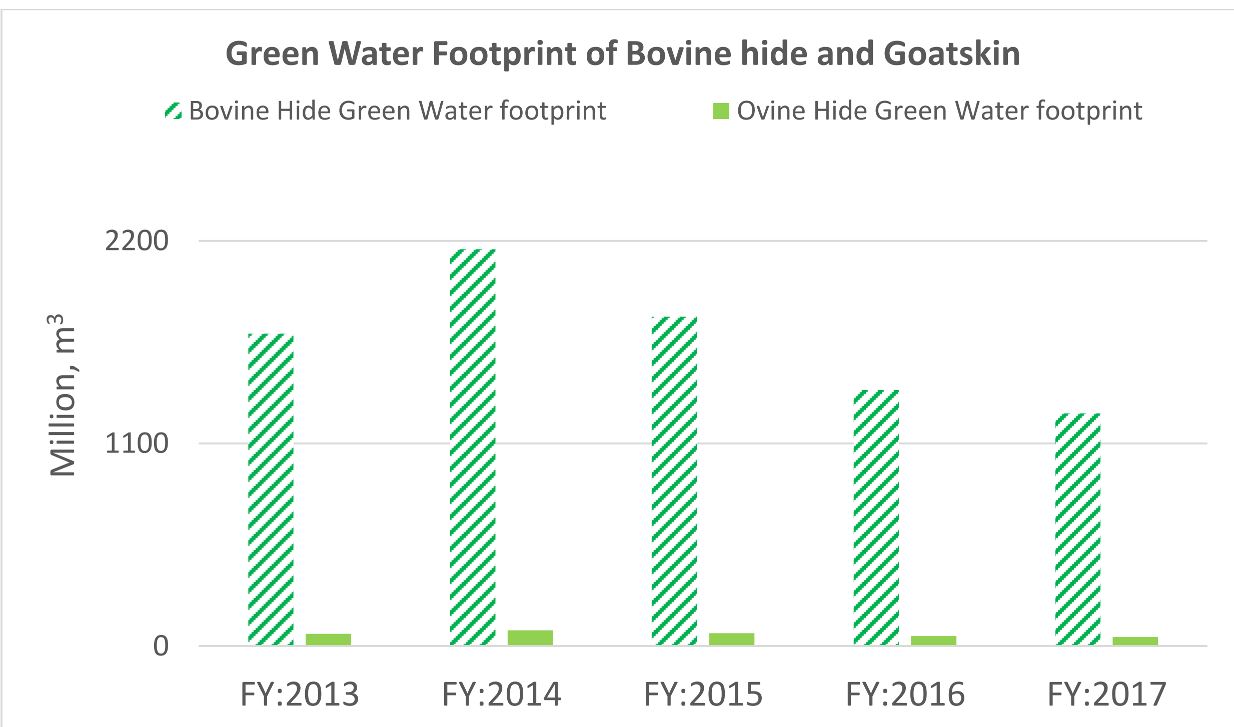


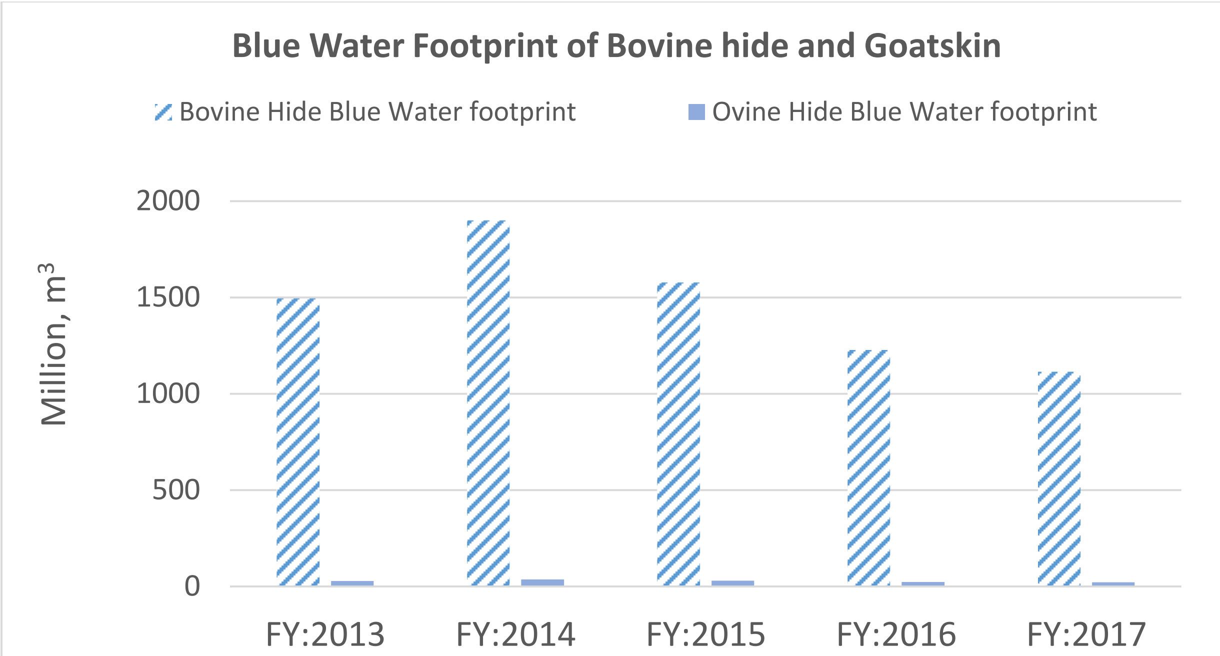
Figure 29: Contribution of water footprint of feed crop in total water footprint

Pasture has 100% green water footprint; Rice Polish (80%), Broken rice (85%) and rice straw (70%) has larger blue water footprint and pulse bran (90%), Maize corn (80%), Maize bran (80%) Pulse offal (90%) and maize stover (80%) has larger grey water footprint contribution in total water footprint of feed crop (See figure 29).

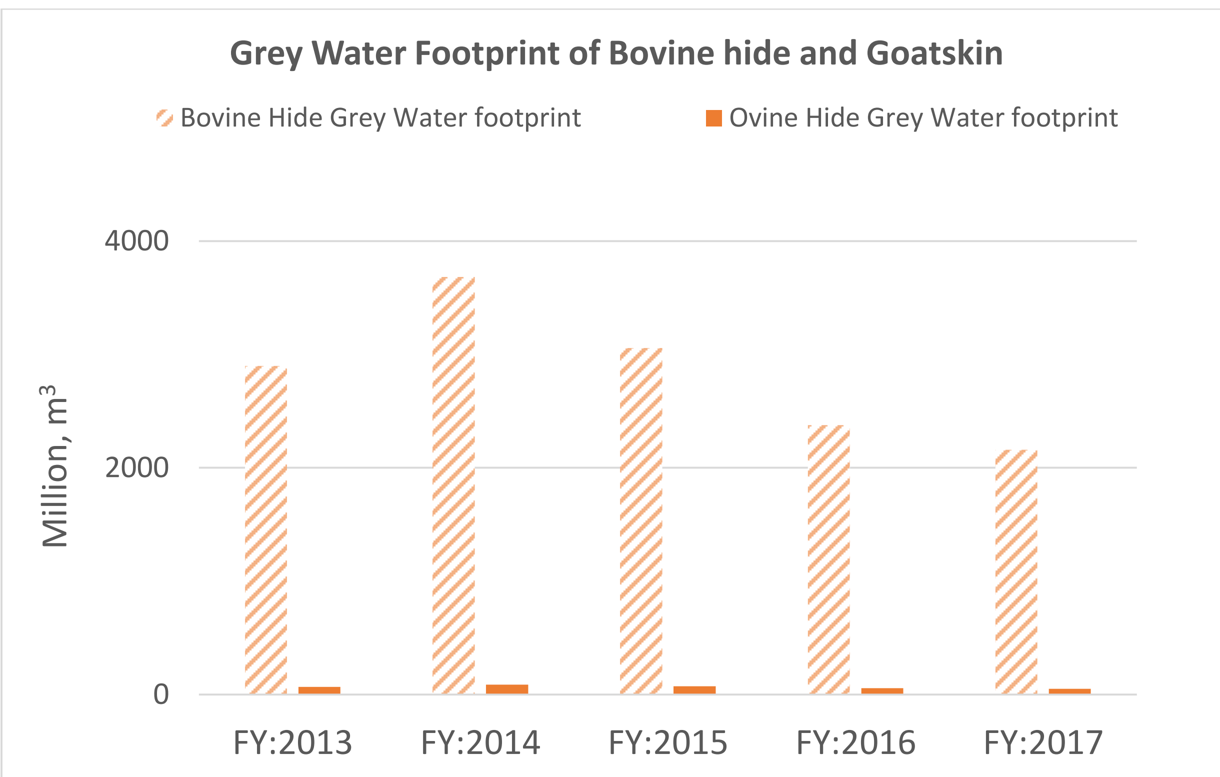
The water footprint of bovine hide is larger than water footprint of ovine hide. The maximum green, blue and grey water footprint of bovine hide has been estimated 2155, 1900 and 3683 million m3 in FY 2014. The green, blue and grey water footprint of ovine hide has been estimated 85, 36 and 87 million m3 in FY 2014 given in figure 30. So, Total water footprint of bovine hide has been estimated 6.08, 7.73, 6.42, 5.00 and 4.53 billion m3 in FY 2013, 2014, 2015, 2016 and 2017. The green water footprint of ovine hide has been estimated 164, 208, 173, 134 and 122 million m3 in FY 2013, 2014, 2015, 2016 and 2017 (See figure 30d). In figure 31 it is indicated that the grey water footprint is almost 40-50%, blue water footprint is almost 10-20% and green water footprint 30-40% in total water footprint.



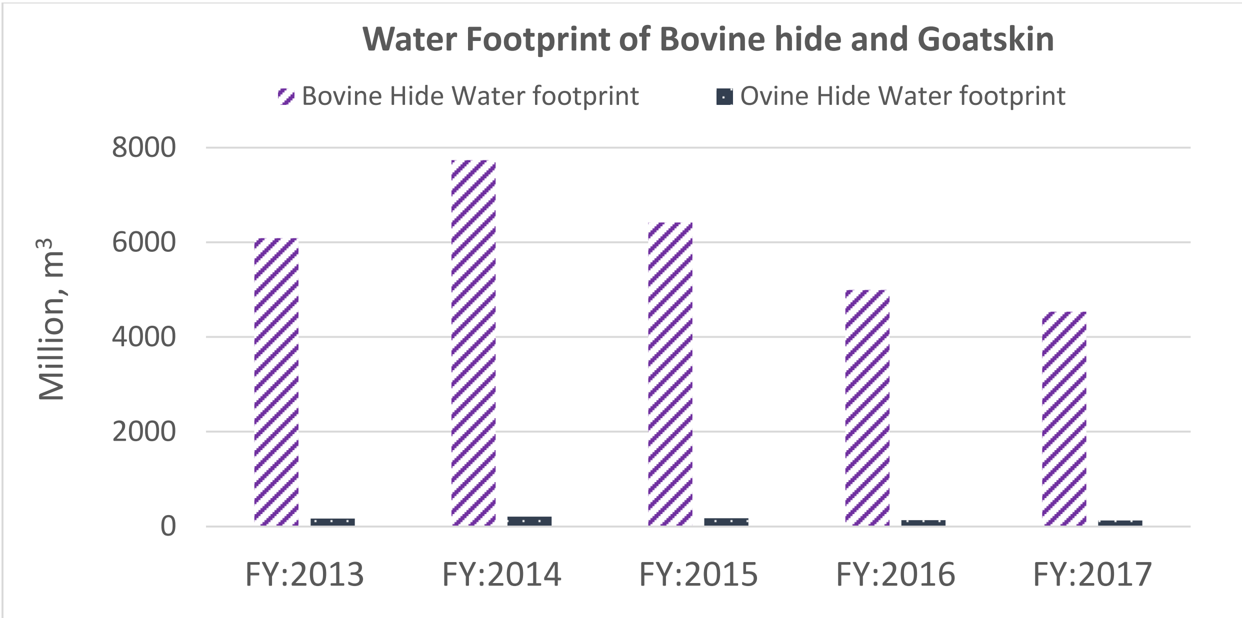
(a)


Blue Water Footprint of Bovine hide and Goatskin
Bovine Hide Blue Water footprint
Ovine Hide Blue Water footprint
2000
1500
1000
500
0
Million, m3
FY:2013
FY:2014
FY:2015
FY:2016
FY:2017

(b)

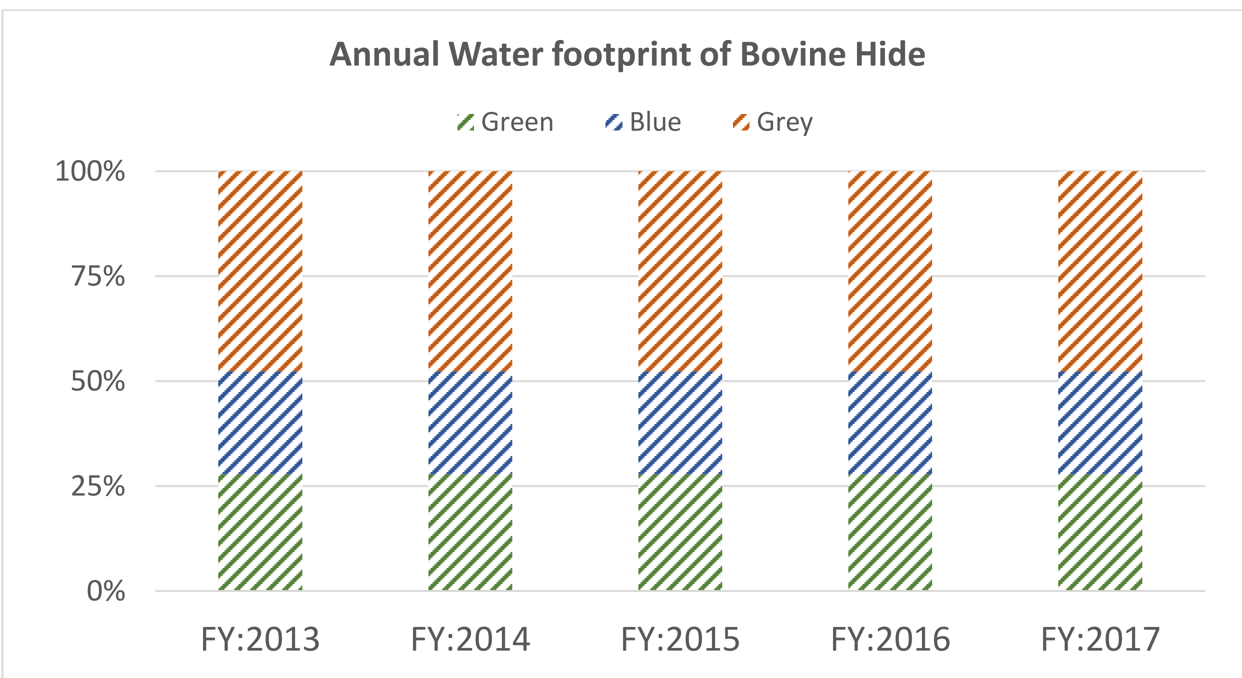

Grey Water Footprint of Bovine hide and Goatskin
Bovine Hide Grey Water footprint
Ovine Hide Grey Water footprint
4000
2000
0
Million, m3
FY:2013
FY:2014
FY:2015
FY:2016
FY:2017

(c)

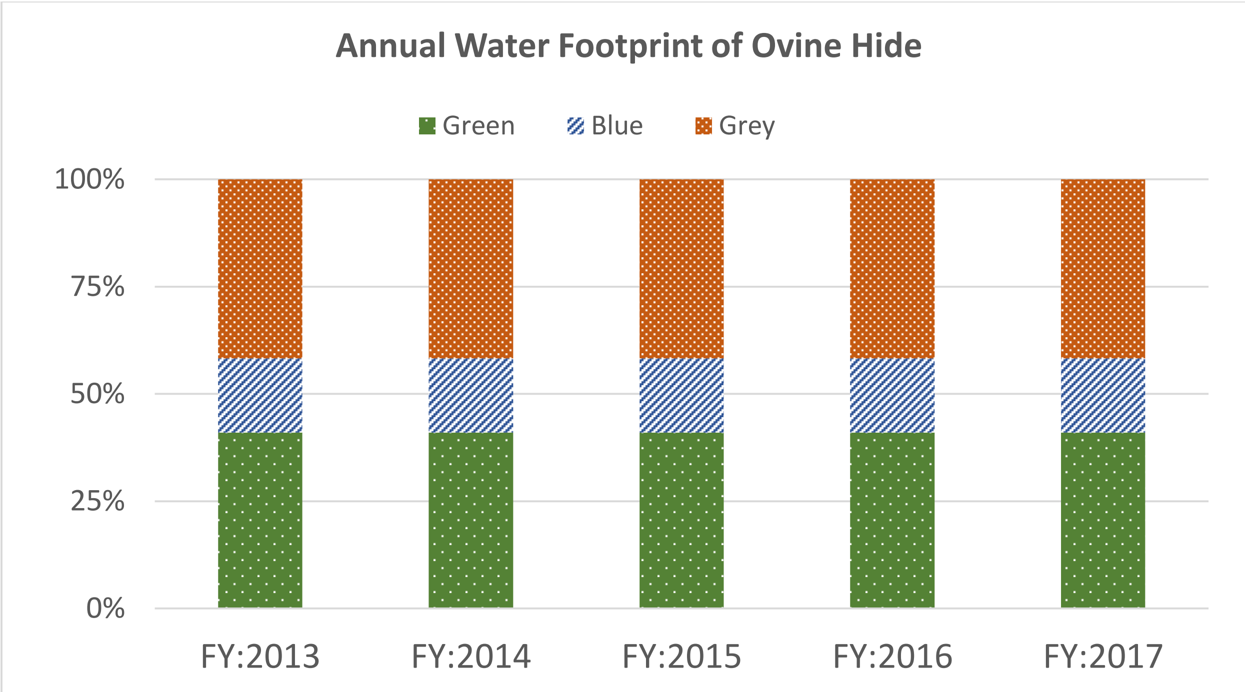


(d)

Figure 30: Annual water footprint of bovine hide and goatskin (a) Annual green water footprint of bovine hide and goatskin (b) Annual blue water footprint of bovine hide and goatskin (c) Annual grey water footprint of bovine hide and goatskin (d) Annual total water footprint of bovine hide and goatskin



(a)

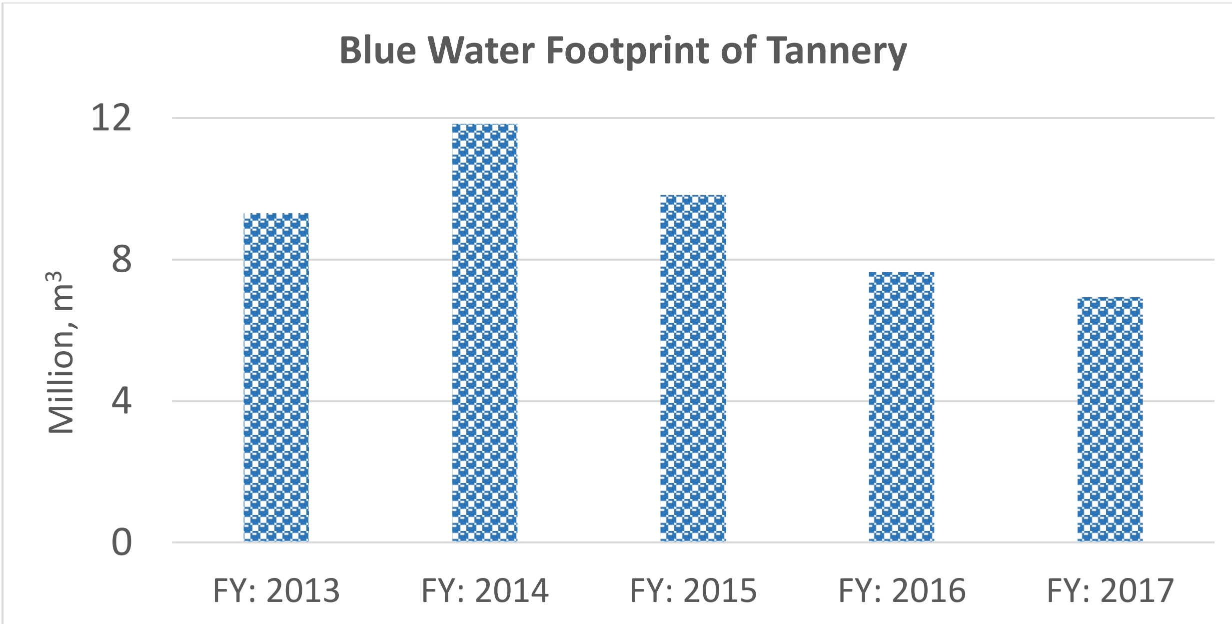


(b)

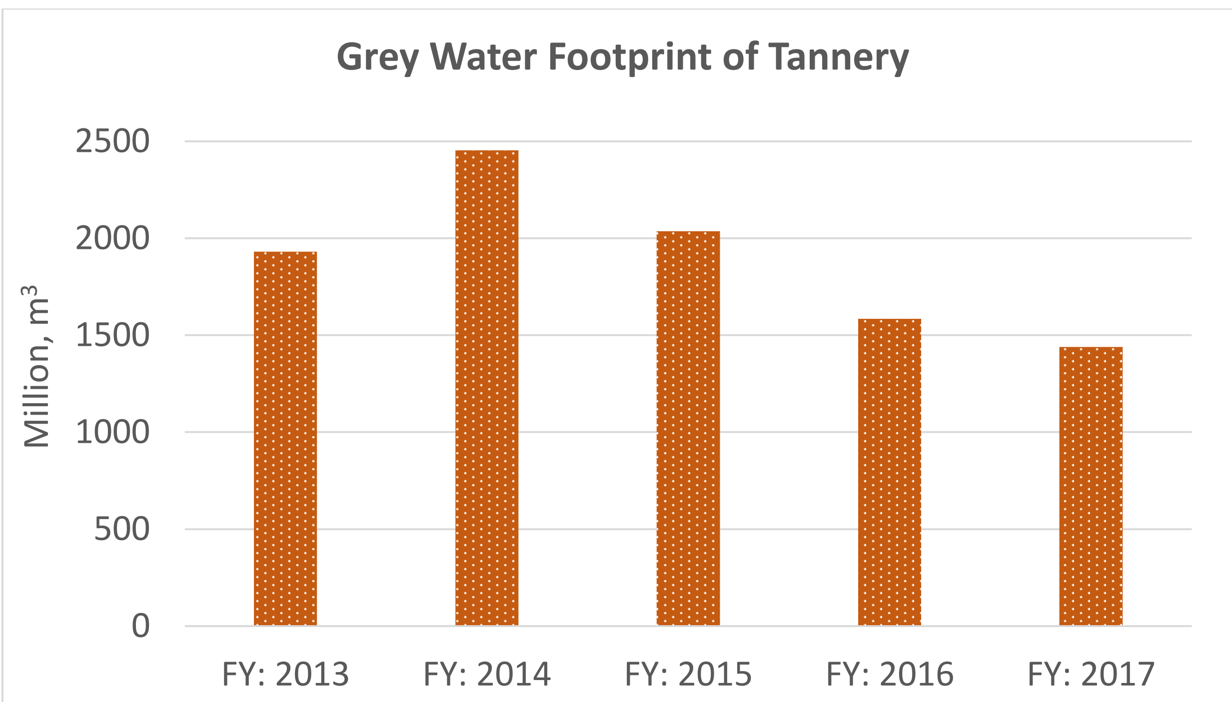
Figure 31: Green, blue and grey water footprint contribution (%) of (a) Bovine hide (b) Goatskin

5.1.2. Contribution of Tanneries in Water Footprint of Leather:

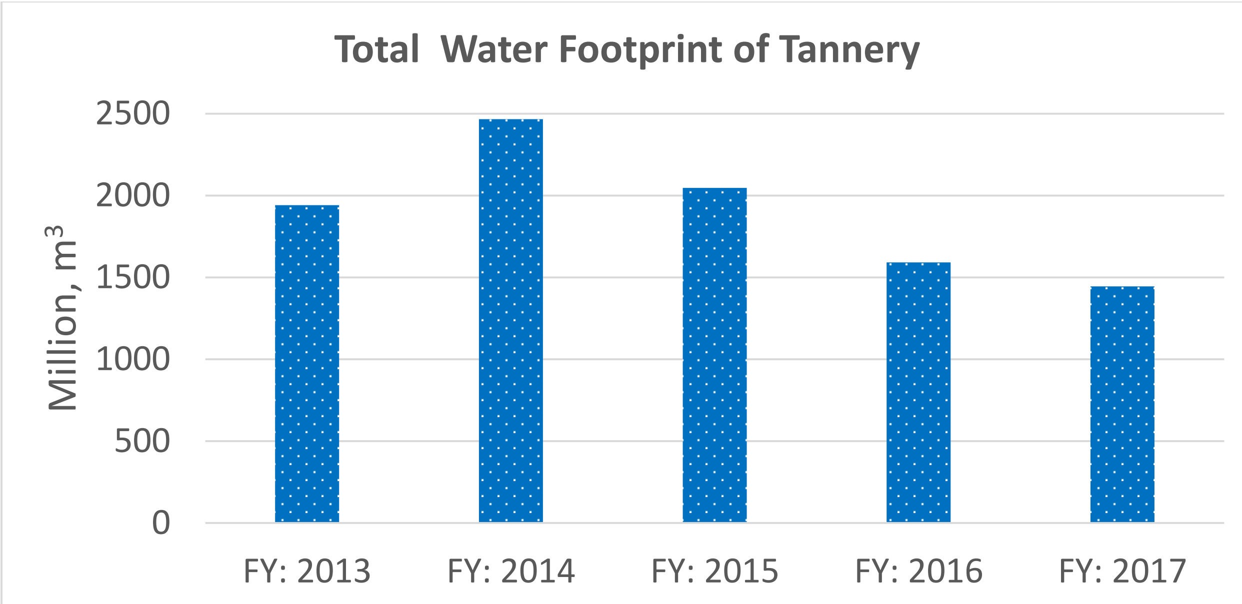
The water footprint of tannery has been estimated to be 1940, 2466, 2046, 1592 and 1446 million m3 in FY 2013, FY 2014, FY 2015, FY 2016 and FY 2017 (See figure 32c). In which Blue water footprint has gone maximum 12 million m^3 in FY 2014 (See figure 32a). But Grey water footprint is almost 207 times higher than blue water footprint of tannery. It has gone up to 2.46 billion m^3 in FY 2014 (See figure 32b). In Appendix E the blue and grey water footprint of tanneries from each stage is given in tabular form.


Blue Water Footprint of Tannery
12
8
4
0
Million, m3
FY: 2013
FY: 2014
FY: 2015
FY: 2016
FY: 2017

(a)


Grey Water Footprint of Tannery
2500
2000
1500
1000
500
0
Million, m3
FY: 2013
FY: 2014
FY: 2015
FY: 2016
FY: 2017

(b)



(c)

Figure 32: Water footprint of tannery (FY 2013-FY2017) (a) Blue water footprint of tannery (FY 2013-FY2017) (b) Grey water footprint of tannery (FY 2013-FY2017) (c) Total water footprint of tannery (FY 2013-FY2017)

Grey water footprint of tannery is so high that it is almost 100% of total water footprint of tannery. It indicates the severity of pollution by tanneries. Larger the grey water higher the pollution level of that industries. Leather production generates highly toxic effluent which has been discussed in the section 5.2. Water footprint of tannery has been analyzed through water footprint of different stages. Maximum contribution in water footprint of leather is the beam house operations and soaking (15%) and liming (28%) are maximum contributed in water footprint because these stages consume and pollute maximum amount of water. From post tanning stages Dyeing (16%) stage has high contribution because of the pollution level of this stage (See figure 34).

Grey water footprint on the other hand depends on the pollutants of the effluent. In the figure 33 tanneries which discharges direct effluent into river has almost 1.5 billion m^3/year grey water footprint but after treatment from CETP it becomes 686 million m^3 /year. And if effluent meets the standards after the treatment grey water footprint gets reduced to 58 million m^3/year.

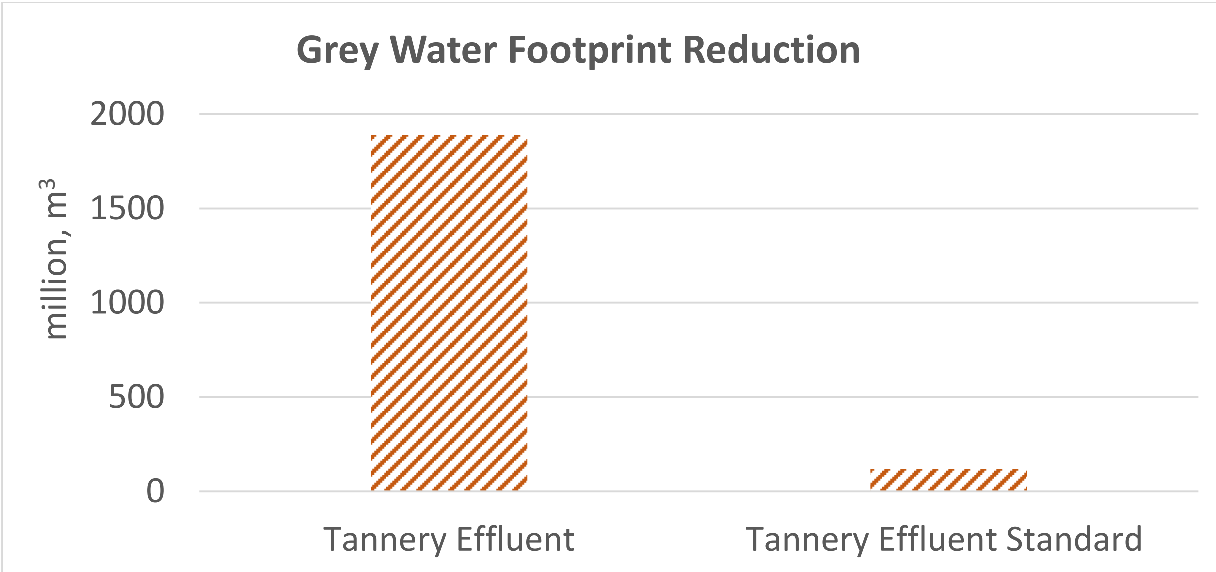


Figure 33: Comparison of tannery grey water footprint of effluent with treatment and without treatment

In water footprint of tannery almost 97% water footprint comes from wet process rest is in mechanical process. And again, water footprint of workers only contributes 20% in the water footprint of tannery so 80% water footprint comes from production of leather in tanneries. In total water footprint of leather and leather products the beam house water footprint is 29% then post tanning 25% (See figure 35). Both the operations are most water consuming and water pollution section in the total production line of making leather products.

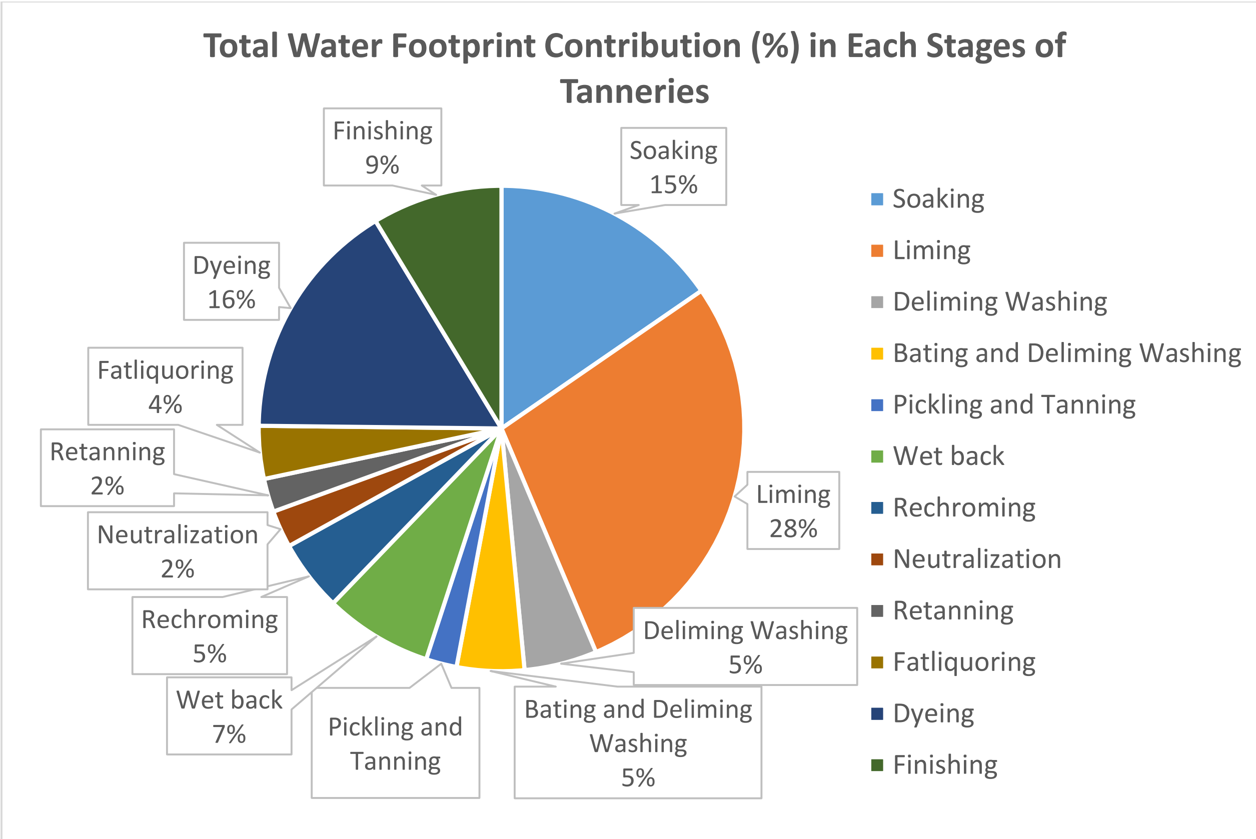


Figure 34: Water footprint contribution in total water footprint of tanneries

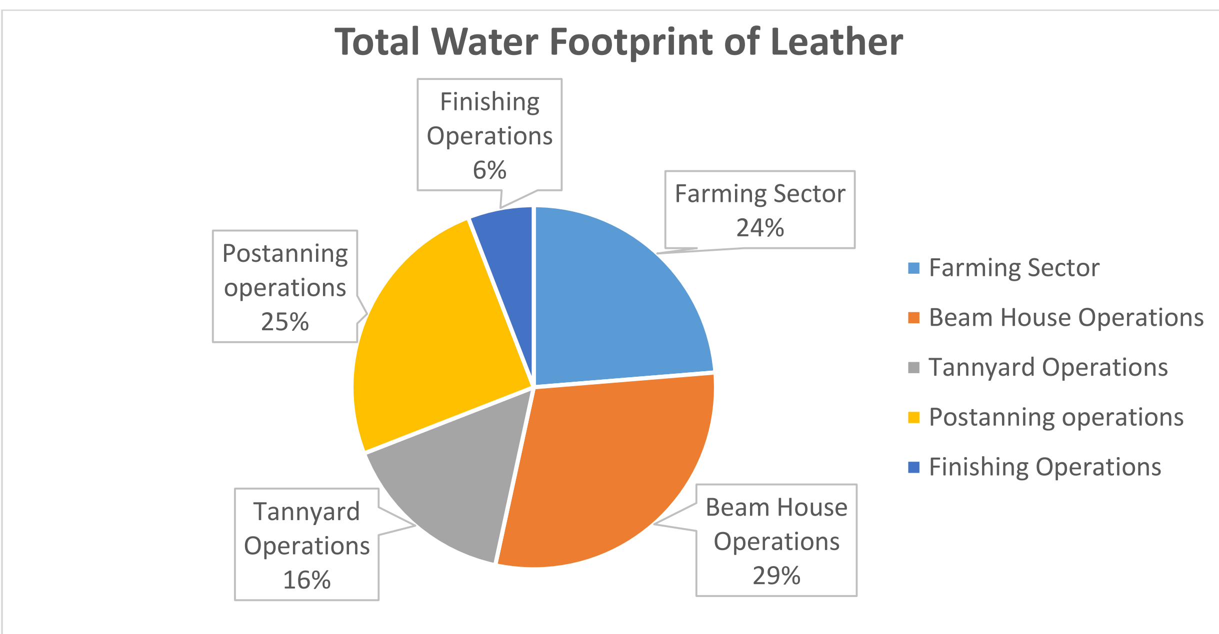


Figure 35: Contribution (%) of water footprint from different operation section in total water footprint of leather

In blue water footprint of leather farming sector alone take 92% of blue water footprint (See figure 36). The main reason for this is Bangladesh is agricultural country and major crops like rice, wheat, maize etc. are cultivated most part of the country and the irrigation also require ground or river water. Tanneries consume very less amount (2-3%) of surface or ground (Blue water) for production. But Beam house (34%), Tan yard (18%) and Post tanning (28%) operations has high grey water footprint for releasing highly toxic effluent (See figure 37). Farming sector also has 13% grey water footprint because the crops are cultivated with fertilizers like UREA, TSP, Gypsum etc. in Bangladesh.

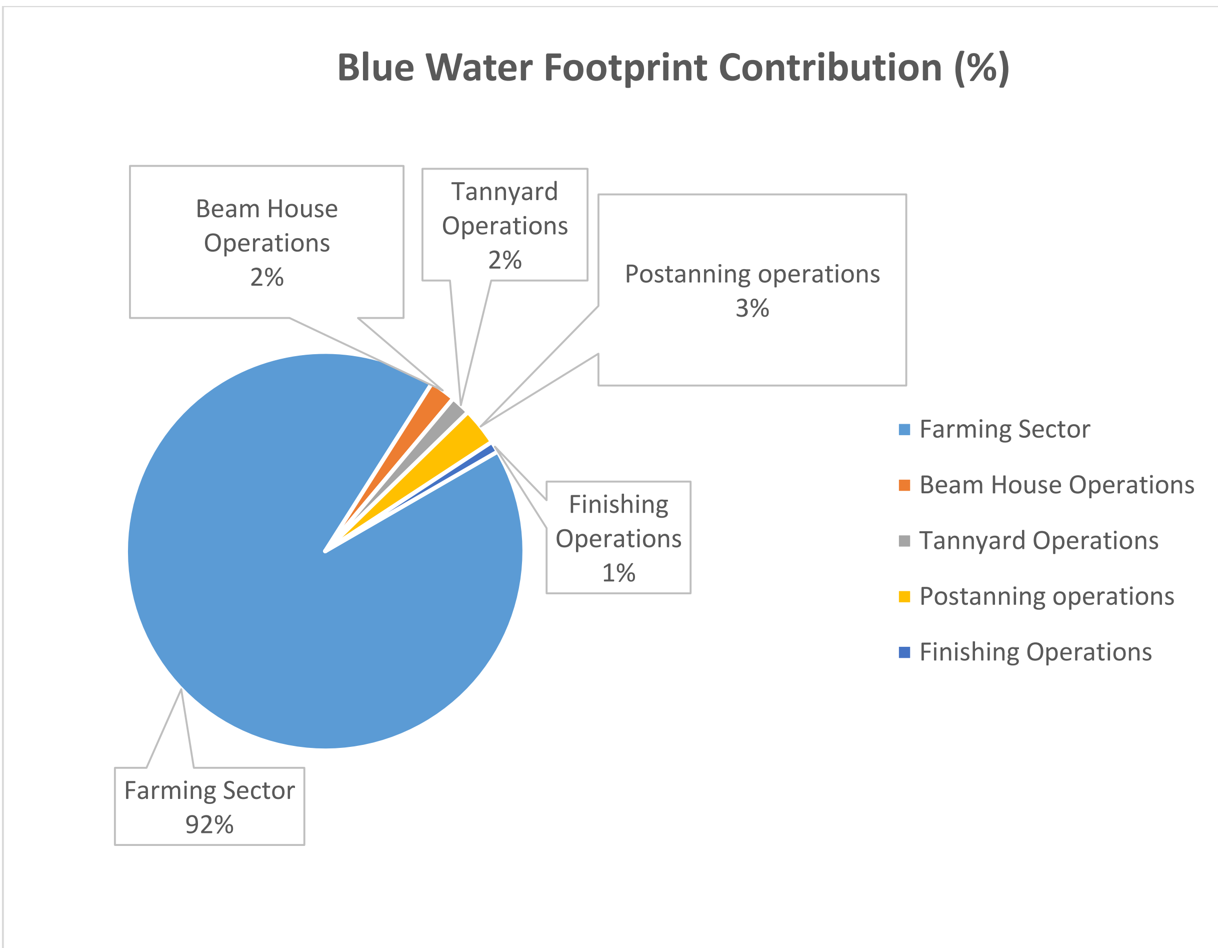


Figure 36: Contribution (%) of blue water footprint from different operation in blue water footprint of leather

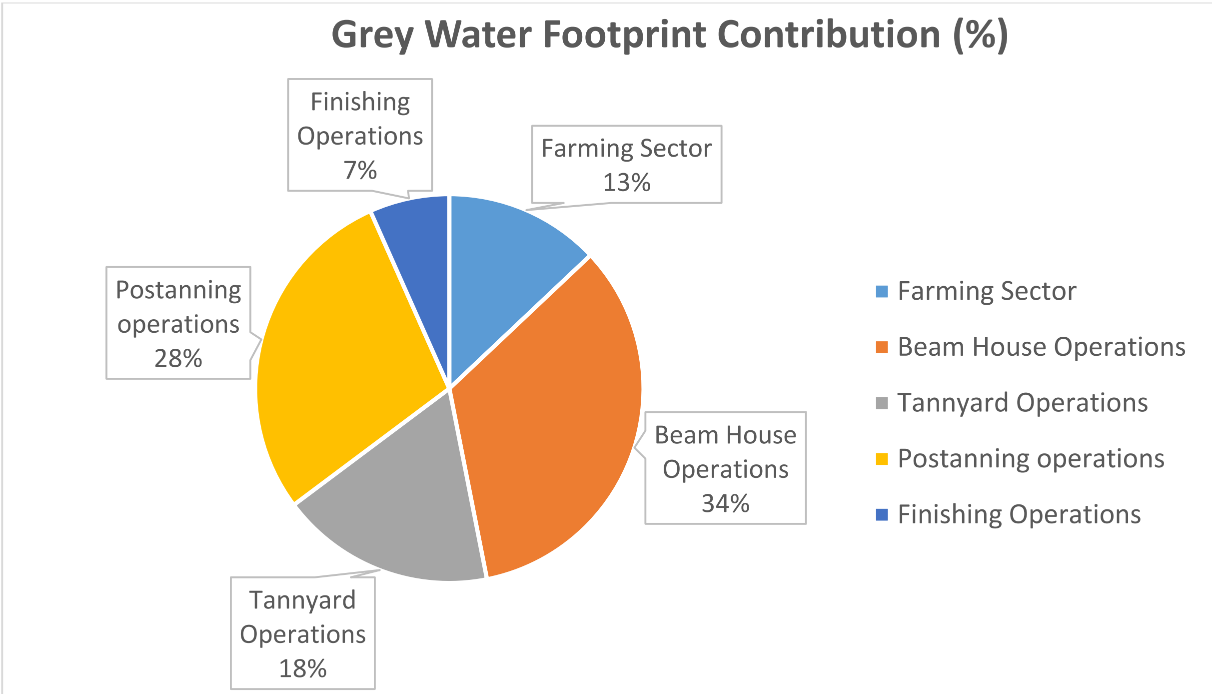


Figure 37: Contribution (%) of grey water footprint from different operation in blue water footprint of leather

But green water footprint of leather and leather products only comes from farming sector as only agriculture utilizes the rain water in Bangladesh and overall, 24% farming sector and 76% tanneries of total water footprint are responsible for the total water footprint of leather and leather products.

5.2. Pollution Impact Assessment

Approximately 30–35 m^3 of effluent is generated per ton of raw hides/skins processed [90] [91]. Almost 15 m^3/ton (52%) effluent generates from beam house and tan yard operations and 14.35 m^3/ton (48%) from post tanning operations. Almost 87% effluent generates from beam house in wet blue production. However, the effluent generation depends on the nature of raw material, finished product and production processes applied [92] [48]. In Appendix C the annual effluent volume, BOD, COD, TDS and TSS data are given in tabular form from FY 2013 to FY 2017.

Tannery effluent is a basic, dark brown colored waste having COD, BOD, TDS, chromium (III) and phenolics with high pH and strong odor [93] [45]. Effluent generates mostly from soaking (21%) and liming (34%) of cured or raw hide. Stages like wet back (8%), retanning (6%) and neutralization (12%) also produces large amount of waste water. Other than that, dyeing (3%), fatliqouring (4%) and rechroming (4%) contributes less in effluent generation. Tan yard operations including deliming, bating and washing (5%), pickling and tanning (3%) produce less amount of effluent (See figure 38).

The characteristics of effluent may vary from stage to stage, tannery to tannery, raw materials and chemicals used, type of final product and the production processes adopted by tanneries [94] [48]. The soaking effluent contains high BOD (21%); TDS (28%); and less COD (16%) and TSS (11%) as it contains high amount of salt, dirt, insecticides and bactericides. But the highest amount BOD (39%); COD (42%); TDS (39%) and TSS (25%) contains effluent generated from liming.

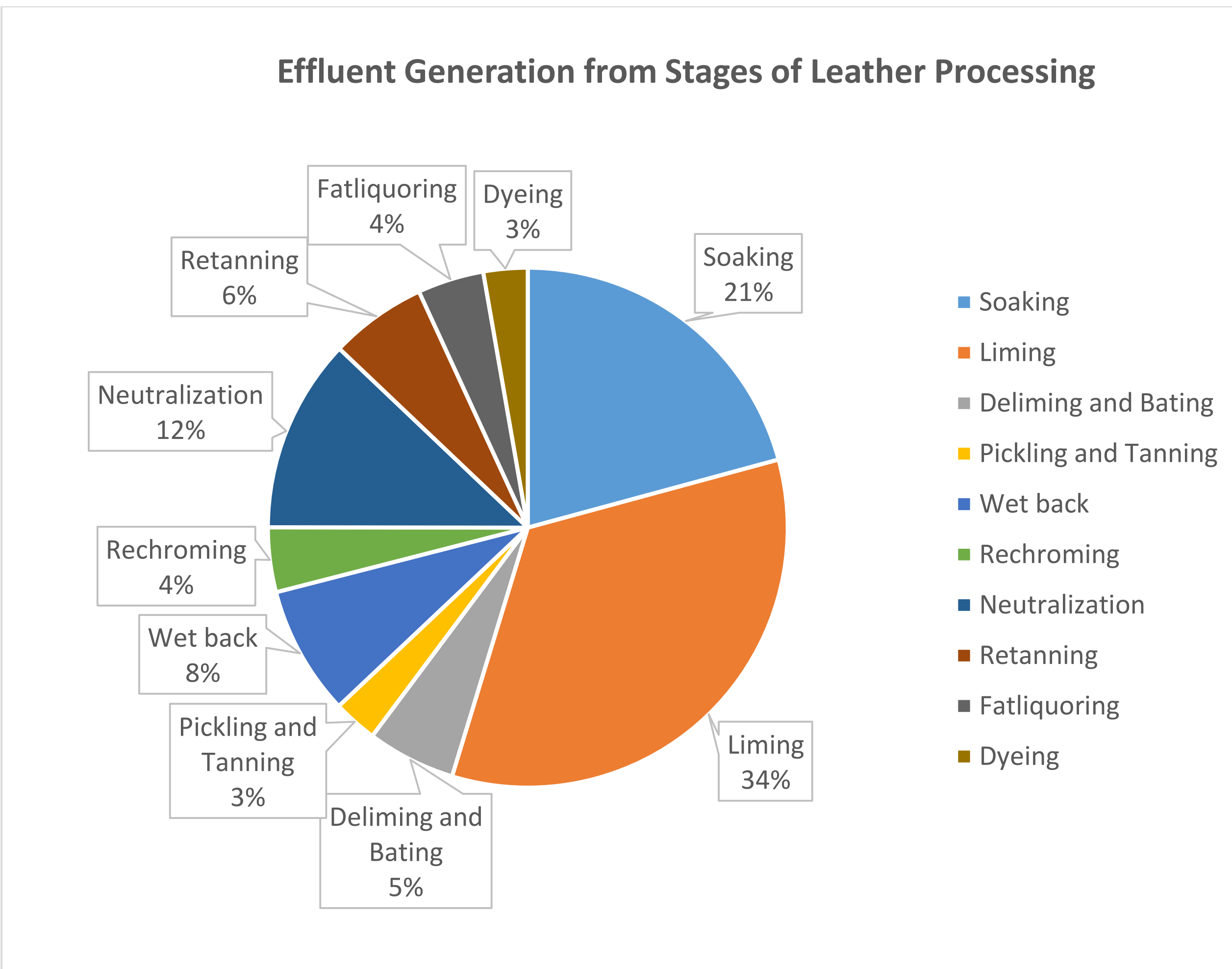
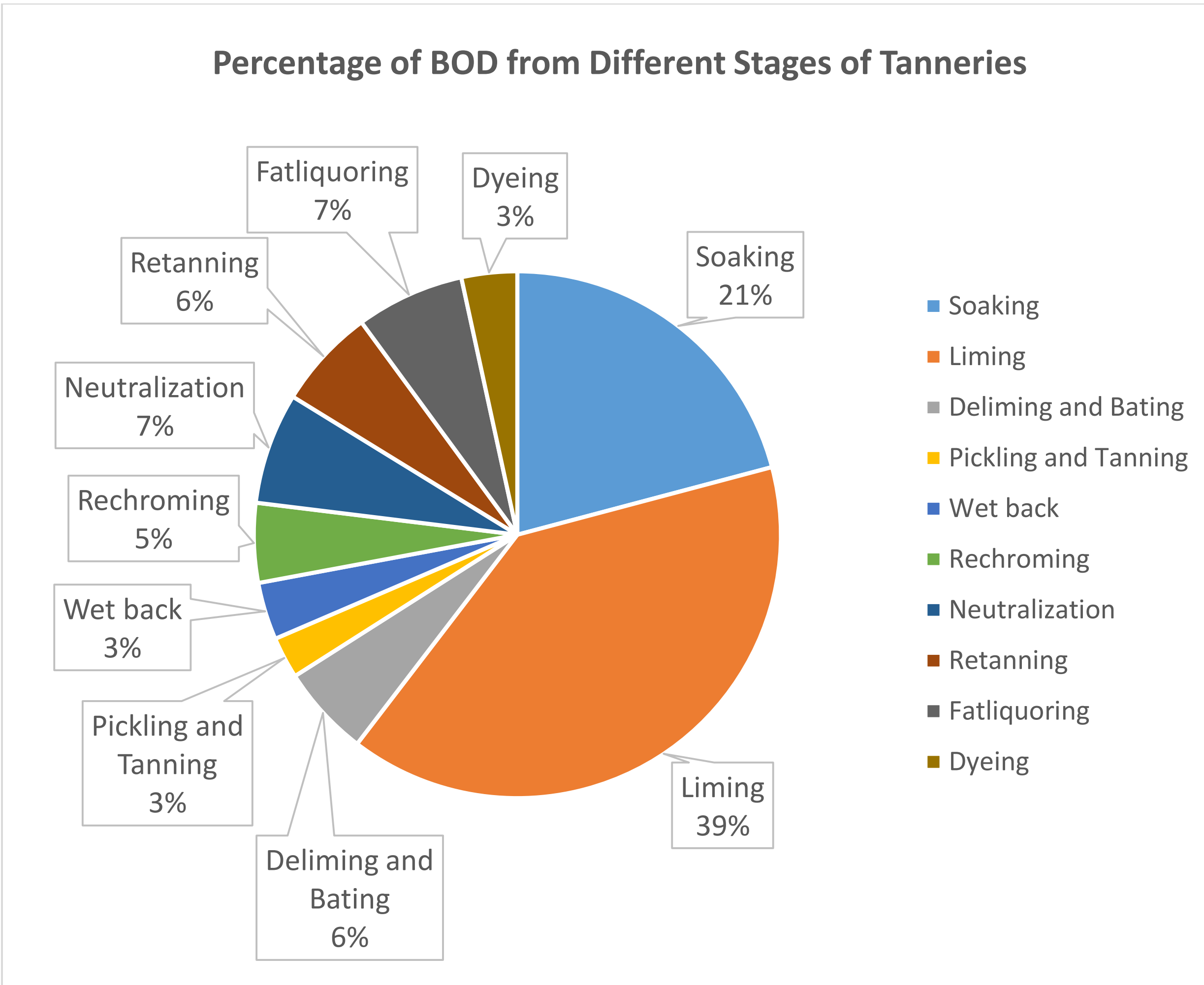
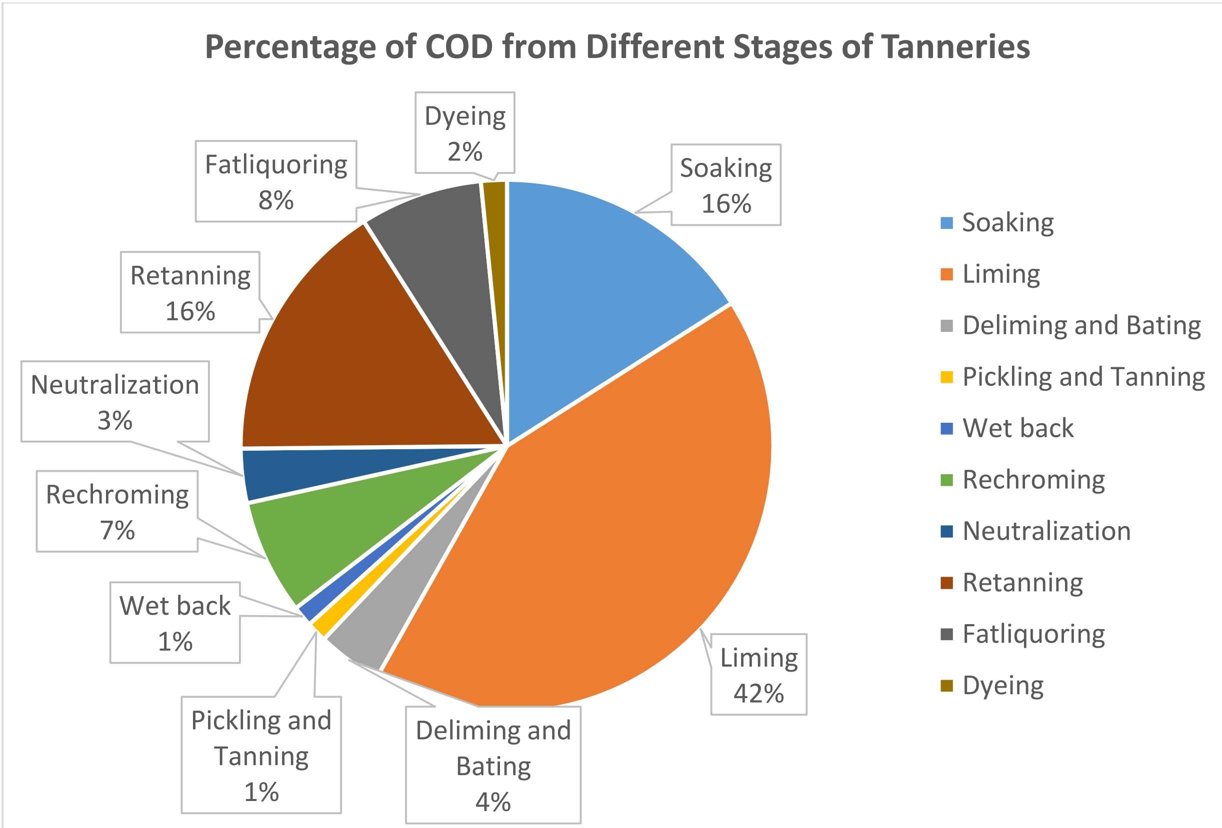


Figure 38: Tannery effluent generation from different stages

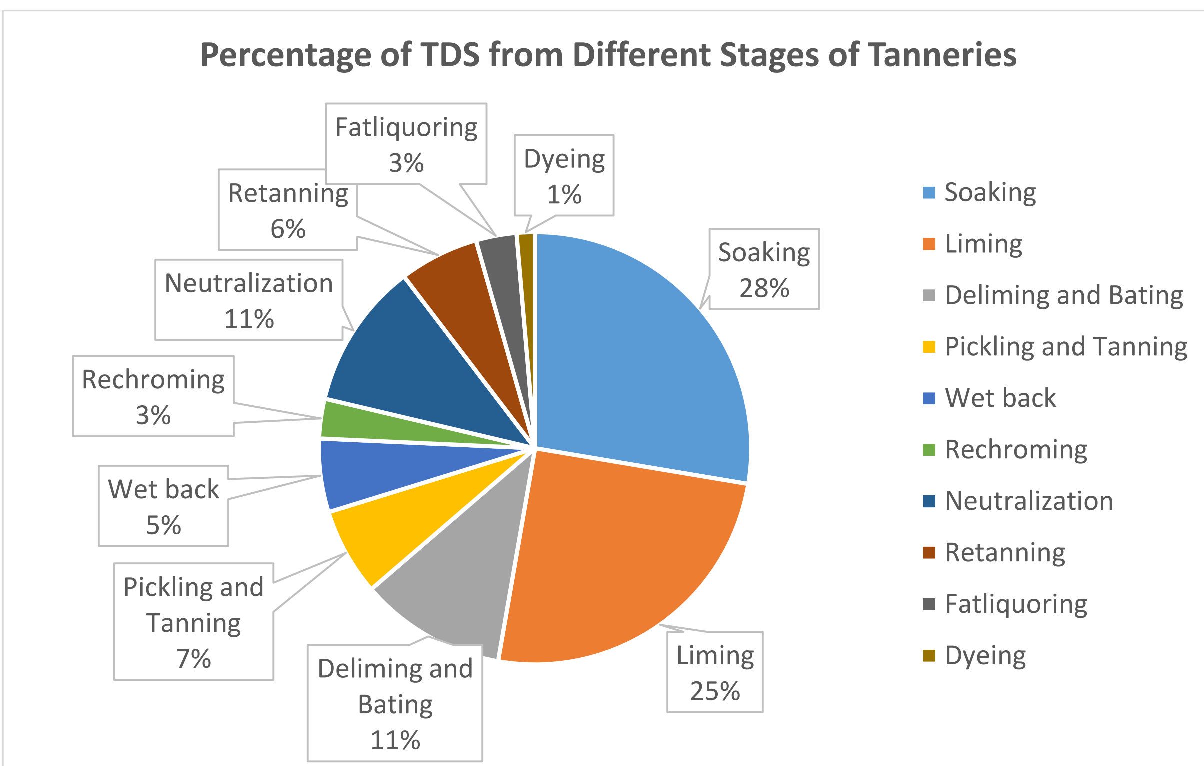
On the other hand, effluent from delime washing, delime and bating contains less amount BOD (6%); COD (4%); TDS (11%) and TSS (10%) and effluent from pickling and tanning also very little contribution in BOD (3%); COD (1%); TDS (7%) and TSS (8%). The retanning effluent streams relatively have a low BOD (6%) and TDS (6%), but high COD (16%) for containing trivalent chromium (III), tannins, sulfonated oils and spent dyes [95](See figure 39).



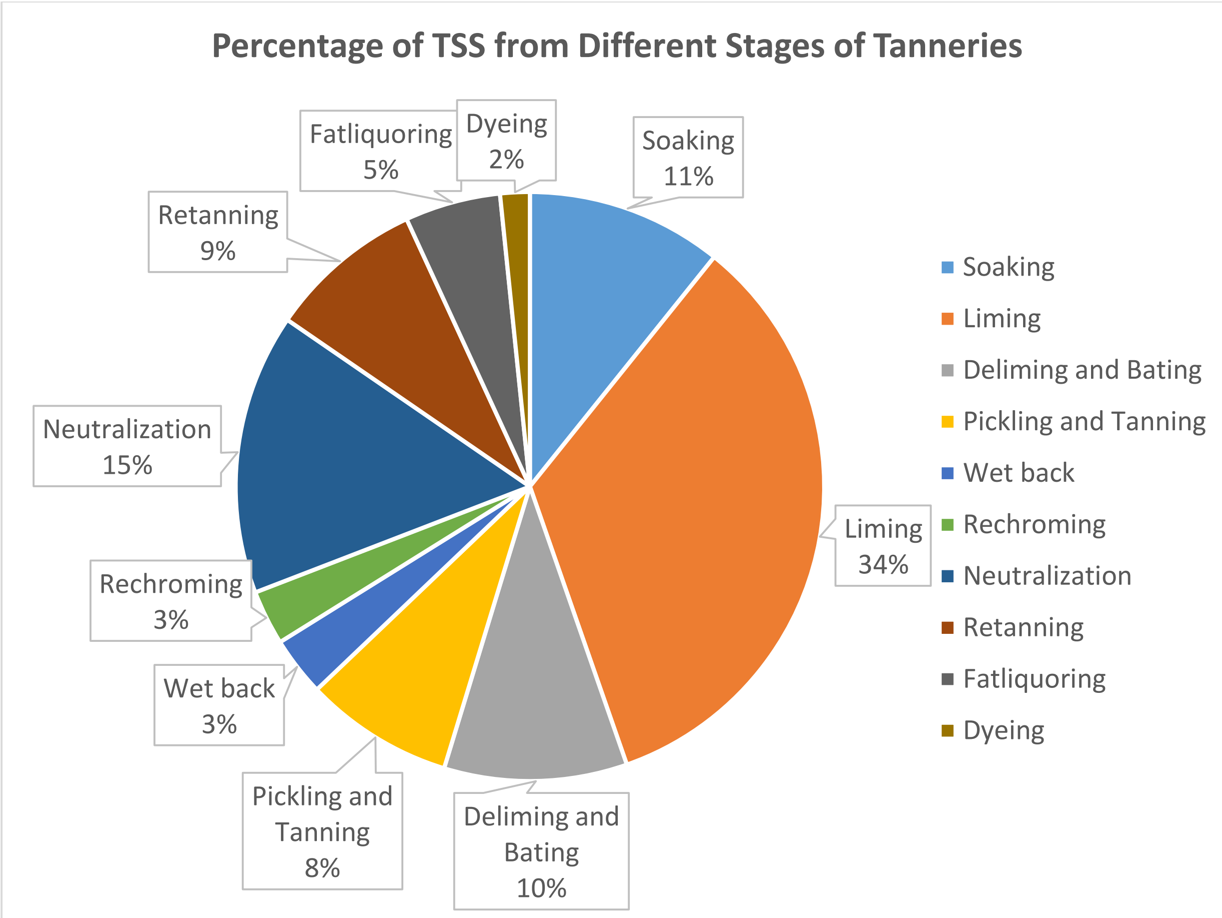
(a)


Percentage of COD from Different Stages of Tanneries
Dyeing 2%
Fatliquoring 8%
Soaking 16%
Retanning 16%
Neutralization 3%
Rechroming 7%
Wet back 1%
Pickling and Tanning 1%
Deliming and Bating 4%
Liming 42%
Soaking
Liming
Deliming and Bating
Pickling and Tanning
Wet back
Rechroming
Neutralization
Retanning
Fatliquoring
Dyeing

(b)


Percentage of TDS from Different Stages of Tanneries
Fatliquoring 3%
Dyeing 1%
Retanning 6%
Soaking 28%
Neutralization 11%
Rechroming 3%
Wet back 5%
Pickling and Tanning 7%
Deliming and Bating 11%
Liming 25%
Soaking
Liming
Deliming and Bating
Pickling and Tanning
Wet back
Rechroming
Neutralization
Retanning
Fatliquoring
Dyeing

(c)



(d)

Figure 39: Characteristics of tannery effluent from different stage of leather processing (a) BOD, (b) COD, (c) TDS, (d) TSS

Biodegradation of the tannery effluent can be explained from this study. The study shows that the ratio BOD_5 and COD is less than 0.5 where Wet back (0.38), Neutralization (0.28) and dyeing (0.29) has high value (See figure 40). These data indicate the effluent of tannery contains low biodegradable substance. These can also imply that the effluent contains complex chemical compounds and toxic in nature.

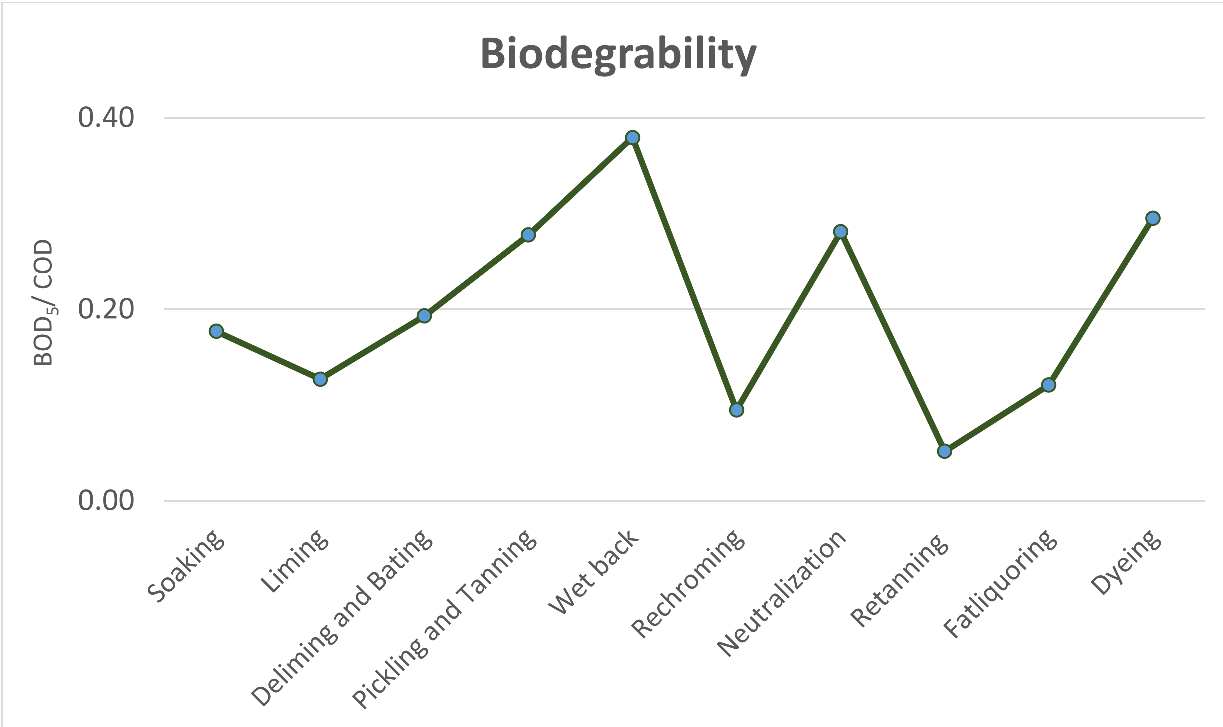


Figure 40: Biodegradability profile of tannery effluents from different stages

Chapter 6: Conclusion and Recommendations

6.1. Conclusion

The thesis gives water footprint and pollution impact assessment which can help to understand the water consumption and pollution intensity of tanneries in Bangladesh by utilizing blue, green, grey water footprint and pollution load data. The research includes detail study of pollution load in each stage of leather production. It also shows that on average almost 3.46 million liters of waste water have been released from tanneries for leather production each year. And it also indicates that the characteristics and load of effluents from each stage are different. Understanding effluent characteristics will reflect both the condition of treated and untreated water released into river. Effluent from liming stage contributes 39% of total BOD and 42 % of total COD and its TDS is 25% and TSS is 34% in waste water. Tannery effluent is highly toxic and contains low biodegradable component as the maximum COD is found to be 142 kg/ton and BOD is18 kg/ton.

Also, water footprint is such a study which can help to understand proper utilization of the water and chemicals in tanneries. Water footprint assessment shows that grey water footprint of leather is almost 40-50%, blue water footprint of leather is almost 10-20% and green water footprint of leather 30-40% in total water footprint of Bangladeshi leather. And highest almost 1 billion m3 or 1000-billion-liter Total water footprint has been estimated for Leather of Bangladesh in FY 2014. So, this study can give an understanding of the water footprint and pollution load of Bangladesh Tanneries. Also, it can help to understand pollution impact of the leather processing in the environment.

6.2. Suggestions for Future Studies

This research shows assessment about water footprint of leather and leather products and it also includes livestock and their feeds and farming water footprint. It also shows the pollution in each stage of leather production in tanneries. But it can help to introduce many future researches as suggested below:

- Grey water footprint for feed crops can be modified. Because feed crops are agricultural products and effluents are produced from sources which are called diffuse source, their data can be more evaluated.

- Water footprint of farming animals can be studied through this research.
- Agriculture is a big sector in this leather study so it can be analyzed more critically through green and grey water footprint of agriculture.
- Reutilization and recycling can be studied through the blue and grey water footprint of tanneries which can be beneficial for the tannery owners.
- Reduction of pollutant (e.g., COD, TSS) can be studied through the pollution load study for leather production in tannery.

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Appendix A

Table A.1: Discharge limits for tannery wastewater into water bodies and sewers in some countries *[46]*

SL. No.	Parameter	Italy		Turkey		Netherlands		Argentina	
		S[a]	S[b]	S[a]	S[b]	S[a]	S[b]	S[a]	S[b]
1.	pH	5.5–9.5	5.5–9.5	6–9	6–10	6–10	6.5–10.0	5.5–10	5.5–10
2.	Temperature °C	30–35	30–35		40		40	45	45
3.	Conductivity (μS/cm)								
4.	Suspended solids (mg/L)	40–80	200	150	350	150	350		
5.	Settleable solids							0.5	0.5
6.	BOD_5 (O_2 mg/L)	40	250	100	250	5	250	50	200
7.	COD (mg/L)	160	500	200	800	[a]	[a]	250	700
8.	TDS (mg/L)								
9.	Sulphide (S^{2-}) (mg/L)	1	2	1	2	[a]	[a]		1
10.	Chrome (III) (mg/L)		4				1		
11.	Chrome (VI) (mg/L)	0.2	0.2	0.3		[a]	[a]		
12.	Total Chrome (mg/L)	2	4	2	5	0.05	2	0.5	2
13.	Chloride (mg/L)	1200	1200			200	[a]	[a]	[a]
14.	Sulfates (mg/L)	1000	1000		1700	3		[a]	1000
15.	Ammonia (mg N/L)	10–15	30					3	10
16.	TKN (mg N/L)				100	[a]	[a]	10	30

Sa: Surface, Sb: Sewer

Table A.2: Discharge limits for tannery wastewater into water bodies and sewers in some countries *[46]*

SL. No.	Parameter	Brazil		Egypt		China		Vietnam	
		S^a	S^b	S^a	S^b	S^a	S^b	S^a	S^b
1.	pH	5.0–9.0		6.0–9.0	6.0–9.0	6.0–9.0	6.0–9.0	5.5–9.0	5.5–9.0
2.	Temperature °C	<40	40	35	0		35	40	45
3.	Conductivity (µS/cm)								
4.	Suspended solids (mg/L)			30	500	70–150	400	100	200
5.	Settleable solids	1.0		[a]	5–10		10		
6.	BOD_5 (O_2 mg/L)	60		20–30	400	20–100	600	50	100
7.	COD (mg/L)			30–40	700	100–300	1000	100	400
8.	TDS (mg/L)			800–1200	2000				
9.	Sulphide (S^{2-}) (mg/L)	0.2	5	1	10	1	10	0.5	1.0
10.	Chrome (III) (mg/L)		5			1.5	2.0	1.0	2.0
11.	Chrome (VI) (mg/L)					0.5	0.5		
12.	Total Chrome (mg/L)	0.5		0.05	5–10	1.5	1.5	2.0	2.0
13.	Chloride (mg/L)			[a]	[a]				
14.	Sulfates (mg/L)			[a]	[a]				
15.	Ammonia (mg N/L)	5		100	100				
16.	TKN (mg N/L)	10							

Sa: Surface, Sb: Sewer

Table A.3: Discharge limits for tannery wastewater into water bodies and sewers in some countries *[46]*

SL. No.	Parameter	Indonesia		Bangladesh		India		Pakistan	
		S^a	S^b	*S^a	S^b	S^a	S^b	S^a	**S^b
1.	pH	6.0–9.0				5.5–9.0	5.5–9.0	6.0–9.0	6.0–9.0
2.	Temperature °C					40–45	40–45	40	
3.	Conductivity (μS/cm)								
4.	Suspended solids (mg/L)	150	150		500	100	600	200	
5.	Settleable solids								
6.	BOD_5 (O_2 mg/L)	150	150		250	30	500	80	
7.	COD (mg/L)	300	300		400	250		150	
8.	TDS (mg/L)					2100	2100		
9.	Sulphide (S^{2-}) (mg/L)				2.0	2	2	1	
10.	Chrome (III) (mg/L)					2	2		
11.	Chrome (VI) (mg/L)					0.1	0.1		
12.	Total Chrome (mg/L)	2	2		2.0	2	2	1	
13.	Chloride (mg/L)					1000	1000	1000	
14.	Sulfates (mg/L)					1000	1000	1000	
15.	Ammonia (mg N/L)	10	10			50	50	40	
16.	TKN (mg N/L)								

*Sa: Surface, Sb: Sewer, *Sa: Bangladesh has no discharge standards for tannery wastewater into surface water, **Sb: Pakistan has no discharge standards for tannery wastewater into sewer*

Appendix B

Table B.1: Monthly humidity (%) data in selected weather stations *[76]*

Station / Month	Barisal	Bogra	Comilla	Chittagong	Dhaka	Dinajpur	Faridpur	Jessore
January	79	76	74	72	65	78	76	77
February	76	67	68	64	55	69	69	71
March	75	63	75	77	55	64	65	65
April	75	70	78	77	63	69	68	67
May	86	81	85	85	78	80	84	79
June	84	79	81	84	76	81	82	81
July	87	81	83	84	77	82	83	82
August	87	85	85	86	80	85	85	84
September	88	82	84	84	81	81	85	84
October	87	83	85	85	78	85	85	85
November	80	78	78	78	66	74	76	75
December	82	0	81	77	72	75	79	78

Table B.2: Monthly humidity (%) data in selected weather stations *[76]*

Month / Station	Khulna	Mymensingh	Patuakhali	Rajshahi	Rangpur	Sylhet	Tangail
January	83	83	77	79	80	74	79
February	77	73	71	74	72	62	73
March	70	73	73	64	66	60	67
April	71	77	77	62	70	69	68
May	82	82	87	80	82	83	81
June	84	85	86	83	81	81	80
July	90	86	89	83	81	83	81
August	91	86	89	86	84	85	84
September	85	84	90	84	82	83	83
October	86	83	89	86	83	81	84
November	75	81	79	76	77	74	77
December	78	83	81	80	80	75	81

Table B.3: Monthly minimum temperature (^oC) data in selected weather stations *[76]*

Month / Station	Barisal	Bogra	Comilla	Chittagong	Dhaka	Dinajpur	Faridpur	Jessore
January	10.5	10.2	10.9	12.7	12.2	8.5	10.4	9.3
February	14.7	15.1	15.7	16.9	17.5	13.8	15	13.5
March	20.9	19.9	20.4	20.8	22	17.9	20.2	19.6
April	24	22.2	23.3	24.3	24.3	21.2	23.7	23.5
May	24.8	24.5	24.1	24.4	24.8	23.8	24.5	25.2
June	26.8	26.8	26.5	26	27.1	26.4	26.7	26.4
July	26.4	26.8	26.1	25.9	27	26.8	26.6	26.4
August	26.2	26.4	25.8	25.7	26.2	26.1	26.3	25.9
September	26	26.5	25.7	25.8	26.3	26	26.2	25.8
October	24.3	23.8	24.1	24.5	24.3	22.3	24.2	23.9
November	17.6	17.4	17.8	20	18.5	15.1	17.5	16
December	14.1	14.1	14.2	16.2	15.6	12.2	14.4	13

Table B.4: Monthly minimum temperature (^oC) data in selected weather stations *[76]*

Month / Station	Khulna	Mymensingh	Patuakhali	Rajshahi	Rangpur	Sylhet	Tangail
January	11.6	10.5	11.7	9.2	9	12	9.8
February	15.5	15.5	15.5	13.5	14.2	15.4	14.2
March	21.1	19.5	20.6	18.2	18.2	19.3	19.4
April	24.1	22.4	23.9	22.6	21.4	22	22.8
May	25.1	23.8	25	24.7	23.7	23.2	24.1
June	27	26.4	26.6	26.5	26.3	25.3	26.2
July	26.6	26.8	26.2	26.6	26.8	25.7	26.4
August	26.2	26.2	26	26.2	26.1	25.5	25.9
September	26.3	26.1	25.7	26.3	26.1	25.5	25.8
October	24.4	23.5	24.4	23.4	23.1	23.6	23.3
November	18.2	16	18.6	26.1	16.8	17.8	16
December	14.9	13.6	14.9	12.6	13.6	15.2	13.3

Table B.5: Monthly maximum temperature (°C) data in selected weather stations *[76]*

Month / Station	Barisal	Bogra	Comilla	Chittagong	Dhaka	Dinajpur	Faridpur	Jessore
January	24.8	23.6	24.5	24.9	24.2	22.5	23.9	24.7
February	29	28.5	28.7	29.2	28.9	27.7	28.5	29.1
March	33.1	32.8	31.8	31.1	33.3	31.9	33.8	34.4
April	34	33.7	32.8	31.9	34.2	32.4	35	35.9
May	31.3	32	30.7	30.3	31.7	31.7	32.1	33.8
June	32.8	34.4	33.4	31.7	33.6	33.8	33.7	34
July	31.3	33.3	32.2	31.3	32.6	33.1	32.5	33.1
August	31.4	32.2	31.8	30.2	32	32.5	32	32.9
September	32	33.6	32.4	31.2	32.6	33.4	32.8	33.3
October	30.8	31.4	31.1	29.9	31.5	30.3	31.8	31.8
November	30	30.7	29.9	28.7	30.1	29.1	29.9	30.7
December	26.8	25.9	26.4	26	26.2	24.3	26.2	27.1

Table B.6: Monthly maximum temperature (°C) data in selected weather stations *[76]*

Month / Station	Khulna	Mymensingh	Patuakhali	Rajshahi	Rangpur	Sylhet	Tangail
January	24.8	23.8	25.6	23.3	22.5	25.5	23.7
February	29	28.3	29.6	27.8	27.2	31.2	28.2
March	33.8	31.8	34.1	33.9	31.5	34.2	32.9
April	35.3	32.4	34.6	36.4	31.2	32.9	34.4
May	33.2	30.5	31.9	33.8	31	30.4	32
June	33.8	33	32.7	35.1	33.3	34	34.3
July	32.7	32.2	31.8	34.3	32.8	33.2	33.3
August	32.6	31.7	31.8	33.4	32.1	32.5	32.5
September	33.1	32.3	32.3	34.3	32.9	32.8	33.2
October	31.6	30.4	31.2	31.3	30	31.4	31.4
November	30.4	29.6	30.2	29.5	28.6	30.1	30.3
December	29.6	25	27.7	25.5	24.3	26.2	25.7

Table B.7: Monthly rainfall (mm) data in selected weather stations *[76]*

Month / Station	Barisal	Bogra	Comilla	Chittagong	Dhaka	Dinajpur	Faridpur	Jessore
January	31	19	16	5	10	5	30	31
February	2	0	1	10	1	5	1	4
March	11	0	13	30	37	3	4	5
April	223	74	195	192	269	57	168	82
May	105	94	209	188	137	79	109	36
June	205	147	442	937	175	380	128	221
July	275	186	282	788	226	435	252	334
August	270	164	373	299	282	106	221	187
September	381	345	178	170	81	349	165	271
October	70	74	115	636	38	91	83	71
November	44	36	102	3	68	1	111	61
December	0	1	3	0	5	0	7	2

Table B.8: Monthly rainfall (mm) data in selected weather stations *[76]*

Month / Station	Khulna	Mymensingh	Patuakhali	Rajshahi	Rangpur	Sylhet	Tangail
January	66	18	7	6	7	10	10
February	18	0	2	6	2	0	0
March	1	1	48	6	2	101	2
April	52	202	80	123	191	659	106
May	63	85	79	17	212	406	171
June	255	241	287	137	369	985	246
July	391	409	392	314	445	700	241
August	254	238	439	179	187	735	204
September	374	221	348	178	405	261	319
October	89	45	142	102	57	502	75
November	80	19	71	101	0	48	94
December	2	0	0	1	0	0	1

Table B.9: Monthly wind (km/d) Data in selected weather stations *[76]*

Month / Station	**Barisal**	**Bogra**	**Comilla**	**Chittagong**	**Dhaka**	**Dinajpur**	**Faridpur**
January	24	48	24	144	48	48	48
February	24	72	24	240	72	48	72
March	24	72	48	168	96	48	48
April	72	72	72	264	96	48	72
May	144	144	120	288	120	72	144
June	48	72	72	240	72	72	72
July	96	120	72	288	120	72	96
August	48	96	72	240	72	72	72
September	24	48	48	168	48	72	48
October	24	24	48	144	24	48	48
November	24	24	24	144	24	24	24
December	24	24	24	120	24	48	24

Table B.10: Monthly wind (km/d) data in selected weather stations *[76]*

Month / Station	**Jessore**	**Khulna**	**Patuakhali**	**Rajshahi**	**Rangpur**	**Sylhet**	**Tangail**
January	24	24	48	48	24	96	48
February	120	24	48	72	48	120	48
March	120	24	48	72	48	120	48
April	192	48	72	96	72	144	72
May	408	96	144	120	72	144	96
June	192	24	72	72	48	120	72
July	192	48	96	96	72	120	96
August	168	48	48	96	48	120	72
September	120	24	48	48	48	120	72
October	96	24	48	72	48	96	48
November	48	24	48	48	48	72	24
December	24	24	24	48	24	72	24

Table B.11: Lengths of crop development stages* for various planting periods and climatic regions (days)

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date
Potato	25	30	30/45	30	115/130	Jan/Nov
	25	30	45	30	130	May
	30	35	50	30	145	April
	45	30	70	20	165	Apr/May
	30	35	50	25	140	Dec
Sweet potato	20	30	60	40	150	April
	15	30	50	30	125	Rainy seas.
Sugarbeet	30	45	90	15	180	March
	25	30	90	10	155	June
	25	65	100	65	255	Sept
	50	40	50	40	180	April
	25	35	50	50	160	May
	45	75	80	30	230	November
	35	60	70	40	205	November
Lentil	20	30	60	40	150	April
	25	35	70	40	170	Oct/Nov
Peas	15	25	35	15	90	May
	20	30	35	15	100	Mar/Apr
	35	25	30	20	110	April
Soybeans	15	15	40	15	85	Dec
	20	30/35	60	25	140	May
	20	25	75	30	150	June
Cotton	30	50	60	55	195	Mar-May
	45	90	45	45	225	Mar
	30	50	60	55	195	Sept
	30	50	55	45	180	April
Sesame	20	30	40	20	100	June
Sunflower	25	35	45	25	130	April/May
Barley/Oats/Wheat	15	25	50	30	120	November
	20	25	60	30	135	March/Apr
	15	30	65	40	150	July
	40	30	40	20	130	Apr
	40	60	60	40	200	Nov
	20	50	60	30	160	Dec
Winter Wheat	20[2]	60[2]	70	30	180	December
	30	140	40	30	240	November
	160	75	75	25	335	October
Grains (small)	20	30	60	40	150	April
	25	35	65	40	165	Oct/Nov

Maize (grain)	30	50	60	40	180	April
	25	40	45	30	140	Dec/Jan
	20	35	40	30	125	June
	20	35	40	30	125	October
	30	40	50	30	150	April
	30	40	50	50	170	April
Maize (sweet)	20	20	30	10	80	March
	20	25	25	10	80	May/June
	20	30	50/30	10	90	Oct/Dec
	30	30	30	103	110	April
	20	40	70	10	140	Jan
Millet	15	25	40	25	105	June
	20	30	55	35	140	April
Sorghum	20	35	40	30	130	May/June
	20	35	45	30	140	Mar/April
Rice	30	30	60	30	150	Dec; May
	30	30.	80	40	180	May
Alfalfa, total season [4]	10	30	var.	var.	var.	
Alfalfa [4] 1st cutting cycle	10	20	20	10	60	Jan Apr (last - 4°C)
	10	30	25	10	75	
Alfalfa [4], other cutting cycles	5	10	10	5	30	Mar
	5	20	10	10	45	Jun
Bermuda for seed	10	25	35	35	105	March
Bermuda for hay (several cuttings)	10	15	75	35	135	---
Grass Pasture [4]	10	20	--	--	--	
Sudan, 1st cutting cycle	25	25	15	10	75	Apr
Sudan, other cutting cycles	3	15	12	7	37	June
Sugarcane, virgin	35	60	190	120	405	
	50	70	220	140	480	
	75	105	330	210	720	
Sugarcane, ratoon	25	70	135	50	280	
	30	50	180	60	320	
	35	105	210	70	420	
Banana, 1st yr	120	90	120	60	390	Mar

Banana, 2nd yr	120	60	180	5	365	Feb
Pineapple	60	120	600	10	790	

(Source: FAO)

Table B.12: Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non-stressed, well-managed crops in subhumid climates (RH_{min}= 45%, u_2 = 2 m/s) for use with the FAO Penman-Monteith ET_o.

Crop	$K_{c\,ini}$[1]	$K_{c\,mid}$	$K_{c\,end}$	Maximum Crop Height (h) (m)
1. Roots and Tubers	**0.5**	**1.10**	**0.95**	
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Sugar Beet	0.35	1.20	0.70[5]	0.5
2. Legumes *(Leguminosae)*	**0.4**	**1.15**	**0.55**	
Beans, green	0.5	1.05[2]	0.90	0.4
Beans, dry and Pulses	0.4	1.15[2]	0.35	0.4
Chick pea		1.00	0.35	0.4
Green Gram and Cowpeas		1.05	0.60-0.35[6]	0.4
Groundnut (Peanut)		1.15	0.60	0.4
Lentil		1.10	0.30	0.5
Peas				
- Fresh	0.5	1.15[2]	1.10	0.5
- Dry/Seed		1.15	0.30	0.5
Soybeans		1.15	0.50	0.5-1.0
3. Fibre Crops	**0.35**			
Cotton		1.15-1.20	0.70-0.50	1.2-1.5
4. Oil Crops	**0.35**	**1.15**	**0.35**	
Rapeseed, Canola		1.0-1.15[9]	0.35	0.6
Safflower		1.0-1.15[9]	0.25	0.8
Sesame		1.10	0.25	1.0
Sunflower		1.0-1.15[9]	0.35	2.0
5. Cereals	**0.3**	**1.15**	**0.4**	
Spring Wheat		1.15	0.25-0.4[10]	1
Winter Wheat				
- with frozen soils	0.4	1.15	0.25-0.4[10]	1
- with non-frozen soils	0.7	1.15	0.25-0.4[10]	

Maize, Field (grain) *(field corn)*		1.20	0.60-0.35[11]	2
Maize, Sweet *(sweet corn)*		1.15	1.05[12]	1.5
Millet		1.00	0.30	1.5
Sorghum				
- grain		1.00-1.10	0.55	1-2
- sweet		1.20	1.05	2-4
Rice	1.05	1.20	0.90-0.60	1
6. Forages				
Alfalfa Hay				
- averaged cutting effects	0.40	0.95[13]	0.90	0.7
- individual cutting periods	0.40[14]	1.20[14]	1.15[14]	0.7
- for seed	0.40	0.50	0.50	0.7
Bermuda hay				
- averaged cutting effects	0.55	1.00[13]	0.85	0.35
- Spring crop for seed	0.35	0.90	0.65	0.4
Clover hay, Berseem				
- averaged cutting effects	0.40	0.90[13]	0.85	0.6
- individual cutting periods	0.40[14]	1.15[14]	1.10[14]	0.6
Rye Grass hay				
- averaged cutting effects	0.95	1.05	1.00	0.3
Sudan Grass hay (annual)				
- averaged cutting effects	0.50	0.90[14]	0.85	1.2
- individual cutting periods	0.50[14]	1.15[14]	1.10[14]	1.2
Grazing Pasture				
- Rotated Grazing	0.40	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.30	0.75	0.75	0.10
Turf grass				
- cool season [15]	0.90	0.95	0.95	0.10
- warm season [15]	0.80	0.85	0.85	0.10
7. Sugar Cane	**0.40**	**1.25**	**0.75**	**3**
8. Tropical Fruits and Trees				
Banana				
- 1st year	0.50	1.10	1.00	3
- 2nd year	1.00	1.20	1.10	4

(Source: FAO)

Table B.13: Factors that influencing the leaching-runoff potential of nitrogen. The state of the factor determines the leaching runoff potential, expressed as a score between 0 and 1. A weight per factor shows the importance of each factor.

Nitrogen							
Category	Factor		Leaching run off potential	Very low	Low	High	Very High
			Score (S)	0	0.33	0.67	1
			Weight (W)				
Environmental	Atmosphere	N-deposition (g N m-2yr-1) (see Appendix II Map 1)	10	<0.5	>0.5	<1.5	>1.5
	Soil	Texture (relevant for leaching) (see Appendix II Map 2)	15	Clay	Silt	Loam	Sand
		Texture (relevant for runoff) (see Appendix II Map 2)	10	Sand	Loam	Silt	Clay
		Natural drainage (relevant for leaching) (see Appendix II Map 3)	10	Poorly to very poorly drained	Moderately to imperfectly drained	Well drained	Excessively to extremely drained

		Natural drainage (relevant for runoff) (see Appendix II Map 3)	5	Excessively to extremely drained	Well drained	Moderately to imperfectly drained	Poorly to very poorly drained
	Climate	Precipitation (mm) (see Appendix II Map 5)	15	0-600	600-1200	1200-1800	> 1800
Agricultural practices	N-fixation (kg/ha)		10	0	>0	<60	>60
	Application rate**		10	Very low	Low	High	Very High
	Plant uptake (crop yield)**		5	Very High	High	Low	Very Low
	Management practice		10	Best	Good	Average	Worst

Table B.14: Factors that influencing the leaching-runoff potential of Phosphorus. The state of the factor determines the leaching runoff potential, expressed as a score between 0 and 1. A weight per factor shows the importance of each factor.

Phosphorus							
Category	Factor		Leaching run off potential	Very low	Low	High	Very High
			Score (S)	0	0.33	0.67	1
			Weight (W)				
Environmental factors	Soil	Texture (relevant for leaching) (see Appendix II Map 2)	15	Clay	Silt	Loam	Sand
		Erosion (Appendix II map 9)	20	Low	Moderate	High	Very High
		P-content (g P m-2) (Appendix II map 6)	15	<200	200-400	400-700	>700
	Climate	Rain Intensity	10	Light	Moderate	Strong	Heavy
Agricultural practices	Application rate**		15	Very low	Low	High	Very High
	Plant uptake (crop yield)**		10	Very High	High	Low	Very Low
	Management practice		15	Best	Good	Average	Worst

Table B.15: Factors that influencing the leaching-runoff potential of Metals. The state of the factor determines the leaching runoff potential, expressed as a score between 0 and 1. A weight per factor shows the importance of each factor.

Metals							
Category	Factor		Leaching run off potential	Very low	Low	High	Very High
			Score (S)	0	0.33	0.67	1
			Weight (W)				
Chemical Properties	K_d (L/kg)(Appendix I, contaminant factors)		30	>1000	1000-200	200-50	<50
Environmental factors	Soil	Texture (relevant for leaching) (see Appendix II Map 2)	15	Sand	Loam	Silt	Clay
		Erosion (Appendix II map 9)	20	Low	Moderate	High	Very High
	Climate	Rain Intensity	10	Heavy	Strong	Moderate	Light
Agricultural practices	Site Management	Artificial drainage (relevant for run off) (Appendix II map 4)	20	Poorly to very poorly drained	Moderately to imperfectly drained	Well drained	Excessively to extremely drained

Appendix C

Table C.1: Yearly pollution load of each stage of the leather production in Bangladesh

Soaking					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	1.31×10^{6}	2.56×10^{6}	1.45×10^{7}	1.77×10^{7}	1.04×10^{7}
FY: 2014	1.66×10^{6}	3.26×10^{6}	1.84×10^{7}	2.25×10^{7}	1.32×10^{7}
FY: 2015	1.38×10^{6}	2.70×10^{6}	1.53×10^{7}	1.87×10^{7}	1.09×10^{7}
FY: 2016	1.07×10^{6}	2.10×10^{6}	1.19×10^{7}	1.45×10^{7}	8.51×10^{6}
FY: 2017	9.76×10^{5}	1.91×10^{6}	1.08×10^{7}	1.32×10^{7}	7.74×10^{6}
Average	1.28×10^{6}	2.51×10^{6}	1.42×10^{7}	1.73×10^{7}	1.02×10^{7}
Liming					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	5.20×10^{5}	1.30×10^{6}	3.10×10^{7}	7.65×10^{6}	2.67×10^{7}
FY: 2014	6.61×10^{5}	1.65×10^{6}	3.94×10^{7}	9.72×10^{6}	3.39×10^{7}
FY: 2015	5.48×10^{5}	1.37×10^{6}	3.27×10^{7}	8.07×10^{6}	2.82×10^{7}
FY: 2016	4.26×10^{5}	1.07×10^{6}	2.55×10^{7}	6.28×10^{6}	2.19×10^{7}
FY: 2017	3.87×10^{5}	9.68×10^{5}	2.31×10^{7}	5.70×10^{6}	1.99×10^{7}
Average	5.08×10^{5}	1.27×10^{6}	3.04×10^{7}	7.48×10^{6}	2.61×10^{7}

Table C.2: Yearly pollution load of each stage of the leather production in Bangladesh

Deliming and Bating					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	3.34×10^{5}	6.61×10^{5}	3.43×10^{6}	6.77×10^{6}	9.33×10^{6}
FY: 2014	4.25×10^{5}	8.41×10^{5}	4.36×10^{6}	8.60×10^{6}	1.19×10^{6}
FY: 2015	3.52×10^{5}	6.98×10^{5}	3.61×10^{6}	7.14×10^{6}	9.85×10^{6}
FY: 2016	2.74×10^{5}	5.43×10^{5}	2.81×10^{6}	5.55×10^{6}	7.66×10^{6}
FY: 2017	2.49×10^{5}	4.93×10^{5}	2.55×10^{6}	5.04×10^{6}	6.96×10^{6}
Average	3.27×10^{5}	6.47×10^{5}	3.35×10^{6}	6.62×10^{6}	9.13×10^{6}
Pickling and Tanning					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	1.11×10^{5}	2.01×10^{5}	7.26×10^{5}	2.69×10^{6}	5.07×10^{6}
FY: 2014	1.42×10^{5}	2.56×10^{5}	9.23×10^{5}	3.42×10^{6}	6.44×10^{6}
FY: 2015	1.17×10^{5}	2.12×10^{5}	7.66×10^{5}	2.84×10^{6}	5.34×10^{6}
FY: 2016	9.14×10^{5}	1.65×10^{5}	5.96×10^{5}	2.21×10^{6}	4.16×10^{6}
FY: 2017	8.30×10^{5}	1.50×10^{5}	5.41×10^{5}	2.00×10^{6}	3.78×10^{6}
Average	1.09×10^{5}	1.97×10^{5}	7.11×10^{5}	2.63×10^{6}	4.96×10^{6}

Table C.3: Yearly pollution load of each stage of the leather production in Bangladesh

Wet Back					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	2.17×10^5	3.07×10^5	2.45×10^5	7.55×10^5	6.71×10^5
FY: 2014	2.76×10^5	3.90×10^5	3.11×10^5	9.60×10^5	8.53×10^5
FY: 2015	2.29×10^5	3.24×10^5	2.58×10^5	7.96×10^5	7.08×10^5
FY: 2016	1.78×10^5	2.52×10^5	2.01×10^5	6.19×10^5	5.50×10^5
FY: 2017	1.62×10^5	2.29×10^5	1.82×10^5	5.63×10^5	5.00×10^5
Average	2.12×10^5	3.00×10^5	2.39×10^5	7.39×10^5	6.56×10^5
Rechroming					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	1.63×10^5	3.45×10^5	1.36×10^6	4.07×10^5	6.20×10^5
FY: 2014	2.07×10^5	4.39×10^5	1.72×10^6	5.17×10^5	7.89×10^5
FY: 2015	1.72×10^5	3.64×10^5	1.43×10^6	4.29×10^5	6.54×10^5
FY: 2016	1.34×10^5	2.83×10^5	1.11×10^6	3.34×10^5	5.09×10^5
FY: 2017	1.21×10^5	2.57×10^5	1.01×10^6	3.03×10^5	4.62×10^5
Average	1.59×10^5	3.38×10^5	1.33×10^6	3.98×10^5	6.07×10^5

Table C.4: Yearly pollution load of each stage of the leather production in Bangladesh

Neutralization					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	1.63×10^{5}	1.25×10^{5}	4.51×10^{5}	7.40×10^{5}	9.78×10^{5}
FY: 2014	2.07×10^{5}	1.59×10^{5}	5.74×10^{5}	9.40×10^{5}	1.24×10^{6}
FY: 2015	1.72×10^{5}	1.32×10^{5}	4.76×10^{5}	7.80×10^{5}	1.03×10^{6}
FY: 2016	1.34×10^{5}	1.02×10^{5}	3.70×10^{5}	6.07×10^{5}	8.03×10^{5}
FY: 2017	1.21×10^{5}	9.31×10^{4}	3.37×10^{5}	5.51×10^{5}	7.29×10^{5}
Average	1.59×10^{5}	1.22×10^{5}	4.42×10^{5}	7.24×10^{5}	9.57×10^{5}
Retanning					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	8.14×10^{4}	1.62×10^{5}	3.13×10^{6}	8.18×10^{5}	1.76×10^{6}
FY: 2014	1.03×10^{5}	2.05×10^{5}	3.98×10^{6}	1.04×10^{6}	2.24×10^{6}
FY: 2015	8.59×10^{4}	1.70×10^{5}	3.30×10^{6}	8.63×10^{5}	1.86×10^{6}
FY: 2016	6.68×10^{4}	1.33×10^{5}	2.57×10^{6}	6.71×10^{5}	1.45×10^{6}
FY: 2017	6.07×10^{4}	1.20×10^{5}	2.34×10^{6}	6.10×10^{5}	1.31×10^{6}
Average	7.97×10^{4}	1.58×10^{5}	3.07×10^{6}	8.01×10^{5}	1.72×10^{6}

Table C.5: Yearly pollution load of each stage of the leather production in Bangladesh

Fatliqouring					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	5.57×10^4	1.75×10^5	1.45×10^6	4.17×10^5	1.08×10^6
FY: 2014	7.08×10^4	2.22×10^5	1.84×10^6	5.30×10^5	1.38×10^6
FY: 2015	5.87×10^4	1.85×10^5	1.53×10^6	4.40×10^5	1.14×10^6
FY: 2016	4.57×10^4	1.44×10^5	1.19×10^6	3.42×10^5	8.90×10^5
FY: 2017	4.15×10^4	1.30×10^5	1.08×10^6	3.11×10^5	8.08×10^5
Average	5.45×10^4	1.71×10^5	1.42×10^6	4.08×10^5	1.06×10^6
Dyeing					
Year	**Effluent Generation (m3)**	**BOD (kg)**	**COD (kg)**	**TDS (kg)**	**TSS (kg)**
FY: 2013	1.48×10^5	2.04×10^5	3.05×10^5	1.88×10^5	3.36×10^5
FY: 2014	1.89×10^5	2.60×10^5	3.87×10^5	2.39×10^5	4.26×10^5
FY: 2015	1.57×10^5	2.15×10^5	3.21×10^5	1.98×10^5	3.54×10^5
FY: 2016	1.22×10^5	1.68×10^5	2.50×10^5	1.54×10^5	2.75×10^5
FY: 2017	1.11×10^5	1.52×10^5	2.27×10^5	1.40×10^5	2.50×10^5
Average	1.45×10^5	2.00×10^5	2.98×10^5	1.84×10^5	3.28×10^5

Appendix D

Table D.1: Calculation of blue water footprint and green water footprint of rice in Bangladesh

Station	Production (M.Ton)	Depth of water for blue (mm)	Blue water Use (m3/year)	Blue water footprint (m3/ton)	Depth of Green Water Use (mm/year)	Green water use (m3/year)	Green water footprint (m3/ton)
Barisal	226889	1879	114102085	456	258	15672090	63
Bogra	756044	1876	350405213	420	256	47745313	57
Comilla	615555	1799	289259238	426	333	53455028	79
Chittagong	213771	1912	121307133	515	324	20534881	87
Dhaka	200560	1863	87766485	397	238	11208659	51
Dinajpur	717878	1952	340631340	430	230	40096653	51
Faridpur	139740	1747	56531100	367	301	9740661	63
Jessore	654036	1812	287815021	399	284	45104312	63
Khulna	198721	1716	84415869	385	311	15282762	70
Mymensingh	1076409	1842	482201756	406	150	39245169	33
Patuakhali	6380	1772	4795023	682	282	761739	108
Rajshahi	286350	1769	129382852	410	297	21684824	69
Rangpur	572404	1867	250540947	397	148	19869540	31
Sylhet	199832	1752	121058924	550	383	26478723	120
Tangail	682505	1851	307584293	409	286	47510004	63

Table D.2: Calculation of grey water footprint of rice used different fertilizer in Bangladesh

Fertilizer	Application rate (kg/ha)	Area (ha)	Load, L (kg)	fraction of leaching (f)	Run off Amount	Grey Water Amount (m3)
Cow dung	20000		3138940000	0.147	461424180	10253870667
Urea	300		47084100	0.15	7062615	156947000
TSP	97		15223859	0.02	304477	6766159.556
MP	120	156947	18833640	0.083	1563192	34737602.67
Gypsum	112		17578064	0.083	1458979	32421762.49
Zinc	10		1569470	0.65	1020155	34005183333

Table D.3: Water footprint of feed crops derived from rice in Bangladesh

Category	Water Use (m3/year)	Rice straw (m3/ton)	Rice polish (m3/ton)	Broken rice (m3/ton)
Production (ton)	---	3.42×10^7	1.39×10^7	4.62×10^6
Blue Water Footprint	3027797278	82.67	212.62	621.39
Green Water Footprint	414390357	11.32	29.10	85.05
Grey Water Footprint	156947000	4.29	11.02	4.29

Table D.4: Calculation of blue water footprint and green water footprint of wheat in Bangladesh

Station	Production (M.Ton)	Depth of water for blue (mm)	Blue water Use (m3/year)	Blue water footprint (m3/ton)	Depth of Green Water Use (mm/year)	Green water use (m3/year)	Green water footprint (m3/ton)
Barisal	1956	582	597384	277	157	160726	75
Bogra	4283	618	1076739	228	122	212646	45
Comilla	3226	565	794004	223	169	237755	67
Chittagong	7	735	2941	381	100	400	52
Chuadanga	18352	548	3089244	153	182	1026333	51
Dhaka	710	581	174766	223	153	46083	59
Dinajpur	59773	682	13080387	199	83	1587938	24
Faridpur	102805	512	16555930	146	185	5994826	53
Jessore	12339	538	2201570	162	178	729194	54
Khulna	555	476	124786	204	206	53867	88
Mymensingh	4934	571	1112610	205	99	192951	35
Patuakhali	39	561	21331	496	137	5202	121
Rajshahi	92475	541	15934399	156	157	4638421	46
Rangpur	9297	603	1987684	194	73	239105	23
Tangail	17153	571	3837975	203	167	1122912	59
Sylhet	190	635	54603	261	113	9684	46

Table D.5: Calculation of grey water footprint of wheat used different fertilizer in Bangladesh

Fertilizer	Application rate (kg/ha)	Area (ha)	Load, L (kg)	fraction of leaching (f)	Run off Amount	Grey Water Amount (m3)
Urea	220		23662760	0.17	4133095	82661908
TSP	150		16133700	0.02	282583	5651667
MP	100	107558	10755800	0.02	188389	3767778
Gypsum	100		10755800	0.63	6803044	136060870
Borax	7		699127	0.04	29125	582490

Table D.6: Water footprint of feed crops derived from wheat in Bangladesh

Category	Water Use (m3/year)	Wheat Straw (m3/ton)	Wheat Bran (m3/ton)
Production (ton)	---	9.32×10^4	8.29×10^4
Blue Water Footprint	60646351	651	732
Green Water Footprint	16258042	174	196
Grey Water Footprint	88313576	948	1065

Table D.7: Calculation of blue water footprint and green water footprint of maize in Bangladesh

Station	Production (M.Ton)	Depth of water for blue (mm)	Blue water Use (m3/year)	Blue water footprint (m3/ton)	Depth of Green Water Use (mm/year)	Green water use (m3/year)	Green water footprint (m3/ton)
Barisal	329	905	68144	188	236	17764	49
Bogra	58053	927	8944593	140	228	2200048	34
Comilla	34045	862	6102311	163	291	2059684	55
Chittagong	8	1023	4552	516	256	1141	129
Chuadanga	398907	865	41284046	94	287	13687870	31
Dhaka	26287	906	3594061	124	233	925042	32
Dinajpur	445731	1002	57831963	118	191	11044192	22
Faridpur	2136	817	237506	101	280	81271	35
Jessore	1312	868	212899	147	259	63517	44
Khulna	139	772	21883	143	306	8668	57
Mymensingh	2523	904	321963	116	155	55306	20
Patuakhali	183	850	42316	210	249	12374	61
Rajshahi	70243	828	10169448	131	276	3385872	44
Rangpur	114674	925	15526910	123	144	2411097	19
Tangail	3791	896	619953	148	262	181340	43

Table D.8: Calculation of grey water footprint of maize used different fertilizer in Bangladesh

Fertilizer	Application rate (kg/ha)	Area (ha)	Load, L (kg)	fration of leaching (f)	Run off Amount	Grey Water Amount (m3)
Cow dung	5.5		863208.5	0.147	126892	2537833
Urea	464		72823408	0.15	10923511	218470224
TSP	144		22600368	0.02	452007	9040147
MP	113	156947	17735011	0.083	1472006	29440118
Mixed	100		15694700	0.083	1302660	26053202
Gypsum	89		13968283	0.658	9191130	183822604
Zinc	8		1255576	0.658	826169	16523380
Borax	4		627788	0.038	23856	477119
Lime	87		13654389	0.658	8984588	179691759
Insecticides	352		55245344	0.038	2099323	41986461

Table D.9: Water footprint of feed crops derived from maize in Bangladesh

Category	Water Use (m3/year)	Maize Corn (m3/ton)	Maize Bran (m3/ton)	Maize Stover (m3/ton)
Production (ton)	---	2.04×10^{6}	1.63×10^{5}	4.08×10^{6}
Blue Water Footprint	144982549	71	887	36
Green Water Footprint	36135187	18	221	9
Grey Water Footprint	708042848	347	4333	173

Table D.10: Calculation of blue water footprint and green water footprint of pulses in Bangladesh

Station	Production (M.Ton)	Depth of water for blue (mm)	Blue water Use (m3/year)	Blue water footprint (m3/ton)	Depth of Green Water Use (mm/year)	Green water use (m3/year)	Green water footprint (m3/ton)
Barisal	16635	591	13706956	748	533	12370477	675
Bogra	952	638	656525	626	492	506319	482
Chittagong	1136	549	796703	636	601	872475	697
Chuadanga	2235	613	1371801	557	517	1155717	469
Dhaka	1311	626	904447	626	421	608468	421
Dinajpur	221	662	137927	566	451	93974	386
Faridpur	21811	520	10228739	425	528	10366834	431
Jessore	10836	560	5963968	499	511	5448956	456
Khulna	374	475	177303	430	567	211901	514
Mymensingh	765	555	405742	481	473	345788	410
Patuakhali	10377	442	5020939	439	602	6830241	597
Rajshahi	28036	527	10924214	353	528	10958094	355
Rangpur	163	570	82378	458	475	68567	382
Tangail	2218	591	1977903	809	542	1813293	742

Table D.11: Calculation of grey water footprint of pulses used different fertilizer in Bangladesh

Fertilizer	Application rate (kg/ha)	Area (ha)	Load, L (kg)	fraction of leaching (f)	Run off Amount	Grey Water Amount (m3)
Urea	44	98114	4317038	0.65	2806075	62357217
TSP	100		9811450	0.65	6377443	141720947
MP	40		3924580	0.65	2550977	56688379
Boric Acid	7.5		735859	0.65	478308	10629071

Table D.12 : Water footprint of feed crops derived from pulses in Bangladesh

Category	Water Use (m3/year)	Pulse Offal (m3/ton)	Pulse Bran (m3/ton)
Production (ton)	---	835000	6960
Blue Water Footprint	3490370	4	501
Green Water Footprint	3443407	4	495
Grey Water Footprint	67848904	81	9748

Appendix E

Table E.1: Usage rate (%) of water in each stage of leather production in tanneries in Bangladesh

Stages	Sub stages	Usage rate (%) of water
Soaking	Pre soaking	300% of raw weight
Soaking	Main soaking	300% of raw weight
Soaking	Washing	100% of raw weight
Liming	Bath	300% of raw weight
Liming	Washing	600% of raw weight
Chemical Wash	Washing	200% of pelt weight
Deliming and Bating	Bath	100% of pelt weight
Deliming and Bating	Washing	400% of pelt weight
Pickling and Tanning	Bath	100% of pelt weight
Wet back	Bath	200% of wet blue shaved weight
Wet back	Washing	200% of wet blue shaved weight
Rechroming	Bath	100% of wet blue shaved weight
Rechroming	Washing	200% of wet blue shaved weight
Neutralization	Bath	150% of wet blue shaved weight
Neutralization	Washing	150% of wet blue shaved weight
Retanning	Bath	150% of wet blue shaved weight
Fatliquoring	Bath	150% of wet blue shaved weight
Dyeing	Bath	200% of wet blue shaved weight
Dyeing	Top dyeing	200% of wet blue shaved weight
Dyeing	Washing	200% of wet blue shaved weight

Table E.2: Water footprint of soaking stage excluding workers in tannery

Year	Weight of raw hide (kg)	Blue water footprint (m3)	Grey water footprint (m3)	Total water footprint (m3)
Pre-Soaking				
FY: 2013	2.69×10^{8}	8.08×10^{5}	1.85×10^{8}	1.86×10^{8}
FY: 2014	3.43×10^{8}	1.03×10^{5}	2.35×10^{8}	2.36×10^{8}
FY: 2015	2.84×10^{8}	8.53×10^{5}	1.95×10^{8}	1.96×10^{8}
FY: 2016	2.21×10^{8}	6.63×10^{5}	1.52×10^{8}	1.52×10^{8}
FY: 2017	2.01×10^{8}	6.03×10^{5}	1.38×10^{8}	1.38×10^{8}
Average	2.64×10^{8}	7.91×10^{5}	1.81×10^{8}	1.82×10^{8}
Main Soaking				
Year	**Weight of raw hide (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	2.69×10^{8}	8.08×10^{5}	1.34×10^{8}	1.34×10^{8}
FY: 2014	3.43×10^{8}	1.03×10^{6}	1.70×10^{8}	1.71×10^{8}
FY: 2015	2.84×10^{8}	8.53×10^{5}	1.41×10^{8}	1.42×10^{8}
FY: 2016	2.21×10^{8}	6.63×10^{5}	1.10×10^{8}	1.10×10^{8}
FY: 2017	2.01×10^{8}	6.03×10^{5}	9.96×10^{7}	1.00×10^{8}
Average	2.64×10^{8}	7.91×10^{5}	1.31×10^{8}	1.32×10^{8}
Soaking Washing				
Year	**Weight of raw hide (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	2.69×10^{8}	2.69×10^{5}	4.59×10^{7}	4.62×10^{7}
FY: 2014	3.43×10^{8}	3.43×10^{5}	5.84×10^{7}	5.87×10^{7}
FY: 2015	2.84×10^{8}	2.84×10^{5}	4.85×10^{7}	4.87×10^{7}
FY: 2016	2.21×10^{8}	2.21×10^{5}	3.77×10^{7}	3.79×10^{7}
FY: 2017	2.01×10^{8}	2.01×10^{5}	3.42×10^{7}	3.44×10^{7}
Average	2.64×10^{8}	2.64×10^{5}	4.50×10^{7}	4.52×10^{7}

Table E.3: Water footprint of liming stage excluding workers in tannery

Liming Main Bath				
Year	**Weight of raw hide (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	2.69×10^{8}	8.08×10^{5}	1.85×10^{8}	1.86×10^{8}
FY: 2014	3.43×10^{8}	1.03×10^{6}	2.35×10^{8}	2.36×10^{8}
FY: 2015	2.84×10^{8}	8.53×10^{5}	1.95×10^{8}	1.96×10^{8}
FY: 2016	2.21×10^{8}	6.63×10^{5}	1.52×10^{8}	1.52×10^{8}
FY: 2017	2.01×10^{8}	6.03×10^{5}	1.38×10^{8}	$1.38E\times10^{8}$
Average	2.64×10^{8}	7.91×10^{5}	1.81×10^{8}	1.82×10^{8}
Liming Washing				
Year	**Weight of raw hide (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	2.69×10^{8}	1.62×10^{6}	5.06×10^{8}	5.08×10^{8}
FY: 2014	3.43×10^{8}	2.06×10^{6}	6.43×10^{8}	6.45×10^{8}
FY: 2015	2.84×10^{8}	1.71×10^{6}	5.34×10^{8}	5.35×10^{8}
FY: 2016	2.21×10^{8}	1.33×10^{6}	4.15×10^{8}	4.16×10^{8}
FY: 2017	2.01×10^{8}	1.21×10^{6}	3.77×10^{8}	3.78×10^{8}
Average	2.64×10^{8}	1.58×10^{6}	4.95×10^{8}	4.97×10^{8}

Table E.4: Water footprint of deliming and bating, pickling and tanning stage excluding workers in tannery

Deliming Washing				
Year	**Weight of pelt hide (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	1.73×10^{8}	3.46×10^{5}	7.61×10^{7}	7.65×10^{7}
2014	2.20×10^{8}	4.40×10^{5}	9.68×10^{7}	9.72×10^{7}
2015	1.83×10^{8}	3.65×10^{5}	8.03×10^{7}	8.07×10^{7}
2016	1.42×10^{8}	2.84×10^{5}	6.25×10^{7}	6.27×10^{7}
2017	1.29×10^{8}	2.58×10^{5}	5.67×10^{7}	5.70×10^{7}
Average	1.69×10^{8}	3.39×10^{5}	7.45×10^{7}	7.48×10^{7}
Deliming and Bating Washing				
Year	**Weight of pelt hide (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	1.73×10^{8}	3.46×10^{5}	7.04×10^{7}	7.08×10^{7}
2014	2.20×10^{8}	4.40×10^{5}	8.95×10^{7}	9.00×10^{7}
2015	1.83×10^{8}	3.65×10^{5}	7.43×10^{7}	7.46×10^{7}
2016	1.42×10^{8}	2.84×10^{5}	5.78×10^{7}	5.81×10^{7}
2017	1.29×10^{8}	2.58×10^{5}	5.25×10^{7}	5.28×10^{7}
Average	1.69×10^{8}	3.39×10^{5}	6.89×10^{7}	6.92×10^{7}
Pickling and Tanning				
Year	**Weight of pelt hide (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	1.73×10^{8}	1.73×10^{5}	3.22×10^{7}	3.24×10^{7}
2014	2.20×10^{8}	2.20×10^{5}	4.09×10^{7}	4.11×10^{7}
2015	1.83×10^{8}	1.83×10^{5}	3.39×10^{7}	3.41×10^{7}
2016	1.42×10^{8}	1.42×10^{5}	2.64×10^{7}	2.65×10^{7}
2017	1.29×10^{8}	1.29×10^{5}	2.40×10^{7}	2.41×10^{7}
Average	1.69×10^{8}	1.69×10^{5}	3.15×10^{7}	3.17×10^{7}

Table E.5: Water footprint of wet Back and rechroming stage excluding workers in tannery

Wet Back Main Bath				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	1.54×10^{5}	8.84×10^{6}	9.00×10^{6}
2014	9.79×10^{7}	1.96×10^{5}	1.12×10^{7}	1.14×10^{7}
2015	8.12×10^{7}	1.62×10^{5}	9.33×10^{6}	9.49×10^{6}
2016	6.32×10^{7}	1.26×10^{5}	7.25×10^{6}	7.38×10^{6}
2017	5.74×10^{7}	1.15×10^{5}	6.59×10^{6}	6.71×10^{6}
Average	7.53×10^{7}	1.51×10^{5}	8.65×10^{6}	8.80×10^{6}
Wet Back Washing				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	1.54×10^{5}	8.84×10^{6}	9.00×10^{6}
2014	9.79×10^{7}	1.96×10^{5}	1.12×10^{7}	1.14×10^{6}
2015	8.12×10^{7}	1.62×10^{5}	9.33×10^{6}	9.49×10^{6}
2016	6.32×10^{7}	1.26×10^{5}	7.25×10^{6}	7.38×10^{6}
2017	5.74×10^{7}	1.15×10^{5}	6.59×10^{6}	6.71×10^{6}
Average	7.53×10^{7}	1.51×10^{5}	8.65×10^{6}	8.80×10^{6}
Rechroming Main Bath				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	7.70×10^{4}	1.23×10^{7}	1.24×10^{7}
2014	9.79×10^{7}	9.79×10^{4}	1.56×10^{7}	1.57×10^{7}
2015	8.12×10^{7}	8.12×10^{4}	1.30×10^{7}	1.31×10^{7}
2016	6.32×10^{7}	6.32×10^{4}	1.01×10^{7}	1.02×10^{7}
2017	5.74×10^{7}	5.74×10^{4}	9.17×10^{6}	9.22×10^{6}
Average	7.53×10^{7}	7.53×10^{4}	1.20×10^{7}	1.21×10^{7}

Table E.6:Water footprint of rechroming and neutralization stage excluding workers in tannery

Rechroming Washing				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	1.54×10^{5}	2.08×10^{7}	2.09×10^{7}
2014	9.79×10^{7}	1.96×10^{5}	2.64×10^{7}	2.66×10^{7}
2015	8.12×10^{7}	1.62×10^{5}	2.19×10^{7}	2.21×10^{7}
2016	6.32×10^{7}	1.26×10^{5}	1.70×10^{7}	1.72×10^{7}
2017	5.74×10^{7}	1.15×10^{5}	1.55×10^{7}	1.56×10^{7}
Average	7.53×10^{7}	1.51×10^{5}	2.03×10^{7}	2.05×10^{7}
Neutralization Main Bath				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	1.15×10^{5}	1.12×10^{7}	1.13×10^{7}
2014	9.79×10^{7}	1.47×10^{5}	1.42×10^{7}	1.44×10^{7}
2015	8.12×10^{7}	1.22×10^{5}	1.18×10^{7}	1.19×10^{7}
2016	6.32×10^{7}	9.47×10^{4}	9.20×10^{7}	9.29×10^{6}
2017	5.74×10^{7}	8.61×10^{4}	8.36×10^{6}	8.44×10^{6}
Average	7.53×10^{7}	1.13×10^{5}	1.10×10^{7}	1.11×10^{7}
Neutralization Washing				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	1.15×10^{5}	5.98×10^{6}	6.10×10^{6}
2014	9.79×10^{7}	1.47×10^{5}	7.60×10^{6}	7.75×10^{6}
2015	8.12×10^{7}	1.22×10^{5}	6.31×10^{6}	6.43×10^{6}
2016	6.32×10^{7}	9.47×10^{4}	4.91×10^{6}	5.00×10^{6}
2017	5.74×10^{7}	8.61×10^{4}	4.46×10^{6}	4.55×10^{6}
Average	7.53×10^{7}	1.13×10^{5}	5.85×10^{6}	5.97×10^{6}

Table E.7: Water footprint of retanning and fatliqouring stage excluding workers in tannery

Retanning Main Bath				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^7	1.15×10^5	1.55×10^7	1.56×10^7
2014	9.79×10^7	1.47×10^5	1.97×10^7	1.98×10^7
2015	8.12×10^7	1.22×10^5	1.63×10^7	1.65×10^7
2016	6.32×10^7	9.47×10^4	1.27×10^7	1.28×10^7
2017	5.74×10^7	8.61×10^4	1.15×10^7	1.16×10^7
Average	7.53×10^7	1.13×10^5	1.51×10^7	1.53×10^7
Fatliqouring Main Bath				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^7	1.15×10^5	2.45×10^7	2.47×10^7
2014	9.79×10^7	1.47×10^5	3.12×10^7	3.13×10^7
2015	8.12×10^7	1.22×10^5	2.59×10^7	2.60×10^7
2016	6.32×10^7	9.47×10^4	2.01×10^7	2.02×10^7
2017	5.74×10^7	8.61×10^4	1.83×10^7	1.84×10^7
Average	7.53×10^7	1.13×10^5	2.40×10^7	2.41×10^7

Table E.8:Water footprint of dyeing stage excluding workers in tannery

Dyeing Main Bath				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	7.70×10^{4}	4.96×10^{7}	4.97×10^{7}
2014	9.79×10^{7}	9.79×10^{4}	6.31×10^{7}	6.32×10^{7}
2015	8.12×10^{7}	8.12×10^{4}	5.23×10^{7}	5.24×10^{7}
2016	6.32×10^{7}	6.32×10^{4}	4.07×10^{7}	4.08×10^{7}
2017	5.74×10^{7}	5.74×10^{4}	3.70×10^{7}	3.70×10^{7}
Average	7.53×10^{7}	7.53×10^{4}	4.85×10^{7}	4.86×10^{7}
Top Dyeing				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	7.70×10^{4}	3.07×10^{7}	3.08×10^{7}
2014	9.79×10^{7}	9.79×10^{4}	3.90×10^{7}	3.91×10^{7}
2015	8.12×10^{7}	8.12×10^{4}	3.24×10^{7}	3.24×10^{7}
2016	6.32×10^{7}	6.32×10^{4}	2.52×10^{7}	2.52×10^{7}
2017	5.74×10^{7}	5.74×10^{4}	2.29×10^{7}	2.29×10^{7}
Average	7.53×10^{7}	7.53×10^{4}	3.00×10^{7}	3.01×10^{7}
Dyeing Washing				
Year	**Weight of Wet blue shaved weight (kg)**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
2013	7.70×10^{7}	1.54×10^{5}	3.26×10^{7}	3.28×10^{7}
2014	9.79×10^{7}	1.96×10^{5}	4.15×10^{7}	4.16×10^{7}
2015	8.12×10^{7}	1.62×10^{5}	3.44×10^{7}	3.46×10^{7}
2016	6.32×10^{7}	1.26×10^{5}	2.68×10^{7}	2.69×10^{7}
2017	5.74×10^{7}	1.15×10^{5}	2.43×10^{7}	2.44×10^{7}
Average	7.53×10^{7}	1.51×10^{5}	3.19×10^{7}	3.21×10^{7}

Table E.9: Water footprint of worker in each stage of leather production

Beam house Operations				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	8982	2.83×10^{5}	1.14×10^{7}	1.17×10^{7}
FY: 2014	11417	3.60×10^{5}	1.45×10^{7}	1.48×10^{7}
FY: 2015	9474	2.98×10^{5}	1.20×10^{7}	1.23×10^{7}
FY: 2016	7368	2.32×10^{5}	9.35×10^{6}	9.58×10^{6}
FY: 2017	6695	2.11×10^{5}	8.49×10^{6}	8.70×10^{6}
Average		2.77×10^{5}	1.11×10^{7}	1.14×10^{7}
Fleshing				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	877	2.76×10^{4}	1.30×10^{6}	1.33×10^{6}
FY: 2014	1115	3.51×10^{4}	1.65×10^{6}	1.69×10^{6}
FY: 2015	925	2.91×10^{4}	1.37×10^{6}	1.40×10^{6}
FY: 2016	720	2.27×10^{4}	1.07×10^{6}	1.09×10^{6}
FY: 2017	654	2.06×10^{4}	9.69×10^{5}	9.90×10^{5}
Average		2.70×10^{4}	6.36×10^{6}	6.39×10^{6}
Tan yard Operations				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	1804	5.68×10^{4}	7.28×10^{7}	7.29×10^{7}
FY: 2014	2294	7.22×10^{4}	9.26×10^{7}	9.27×10^{7}
FY: 2015	1903	6.00×10^{4}	7.68×10^{7}	7.69×10^{7}
FY: 2016	1480	4.66×10^{4}	5.98×10^{7}	5.98×10^{7}
FY: 2017	1345	4.24×10^{4}	5.43×10^{7}	5.43×10^{7}
Average		5.56×10^{4}	7.13×10^{7}	7.13×10^{7}

Table E.10: Water footprint of worker in each stage of leather production

Mechanical Operations (Samming)				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	3243	1.02×10^5	4.11×10^6	4.22×10^6
FY: 2014	4123	1.30×10^5	5.23×10^6	5.36×10^6
FY: 2015	3421	1.08×10^5	4.34×10^6	4.45×10^6
FY: 2016	2661	8.38×10^4	3.38×10^6	3.46×10^6
FY: 2017	2418	7.62×10^4	3.07×10^6	3.14×10^6
Average		1.00×10^5	4.03×10^6	4.13×10^6
Mechanical Operations (Splitting)				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	3243	1.02×10^5	1.31×10^8	1.31×10^8
FY: 2014	4123	1.30×10^5	1.66×10^8	1.67×10^8
FY: 2015	3421	1.08×10^5	1.38×10^8	1.38×10^8
FY: 2016	2661	8.38×10^4	1.07×10^8	1.08×10^8
FY: 2017	2418	7.62×10^4	9.76×10^7	9.77×10^7
Average		1.00×10^5	1.28×10^8	1.28×10^8
Mechanical Operations (Shaving)				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	3243	1.02×10^5	1.31×10^8	1.31×10^8
FY: 2014	4123	1.30×10^5	1.66×10^8	1.67×10^8
FY: 2015	3421	1.08×10^5	1.38×10^8	1.38×10^8
FY: 2016	2661	8.38×10^4	1.07×10^8	1.08×10^8
FY: 2017	2418	7.62×10^4	9.76×10^7	9.77×10^7
Average		1.00×10^5	1.28×10^8	1.28×10^8

Table E.11: Water footprint of worker in each stage of leather production

Post Tanning Operations				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	802	2.53×10^{4}	3.24×10^{7}	3.24×10^{7}
FY: 2014	1019	3.21×10^{4}	4.12×10^{7}	4.12×10^{7}
FY: 2015	846	2.66×10^{4}	3.41×10^{7}	3.42×10^{7}
FY: 2016	658	2.07×10^{4}	2.66×10^{7}	2.66×10^{7}
FY: 2017	598	1.88×10^{4}	2.41×10^{7}	2.42×10^{7}
Average		2.47×10^{4}	3.17×10^{7}	3.17×10^{7}
Mechanical Operations (Setting)				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	3449	1.09×10^{5}	6.83×10^{5}	7.91×10^{5}
FY: 2014	4384	1.38×10^{5}	8.68×10^{5}	1.01×10^{5}
FY: 2015	3638	1.15×10^{5}	7.20×10^{5}	8.35×10^{5}
FY: 2016	2830	8.91×10^{4}	5.60×10^{5}	6.49×10^{5}
FY: 2017	2571	8.10×10^{4}	5.09×10^{5}	5.90×10^{5}
Average		1.06×10^{5}	6.68×10^{5}	7.74×10^{5}
Mechanical Operations (Toggling, Buffing, Dedusting)				
Year	**Number of workers**	**Blue water footprint (m3)**	**Grey water footprint (m3)**	**Total water footprint (m3)**
FY: 2013	3449	3.26×10^{5}	2.05×10^{6}	2.37×10^{6}
FY: 2014	4384	4.14×10^{5}	2.60×10^{6}	3.02×10^{6}
FY: 2015	3638	3.44×10^{5}	2.16×10^{6}	2.50×10^{6}
FY: 2016	2830	2.67×10^{5}	1.68×10^{6}	1.95×10^{6}
FY: 2017	2571	2.43×10^{5}	1.53×10^{6}	1.77×10^{6}
Average		3.19×10^{5}	2.00×10^{6}	2.32×10^{6}

Appendix F

Summary of all the equation used in the calculation of the water footprint of leather:

Biological oxygen demand:

$BOD = [(DO\ sample - DO_5\ sample) – (DO\ blank – DO_5\ blank)] \times (f/V)$ …………..………… (1)

Water footprint of leather:

$WF = WF_{blue} + WF_{green} + WF_{grey}$ ……………………………………..……….……………… (2)

$WF = WF_{direct} + WF_{indirect}$ ………………………………...……………………..………… (3)

Water footprint of feed crop:

$$ET_o = \frac{0.408\ \Delta(R_n - G) + \gamma \frac{900}{T+273} u^2 (e_s - e_a)}{\Delta + \gamma\ (1 + 0.34\ u^2)}$$ ………………..……………………………….. (4)

$P_{eff} = (P \times (125 – 0.2 \times 3\ X\ P))/\ 125$ for $P <= 250/3$ ……………….……………… (5)

$P_{eff} = 125/3 + 0.1\ X\ P$ for $P > 250/3$ …………………………….……… (6)

$IR = \max(0, WD – WA)$ ……………………………………………...……...…………… (7)

$CWD_{green} = \min(WD, P_{eff})$ ……………………………………………………….……...…… (8)

$CWD_{blue} = \max(0, IR\ (WD-WA))$ …………………………………………………..…………… (9)

$$WF_{grey} = \frac{L}{L_{crit}} \times R$$ ………………………..……………………..………...…………….…….… (10)

$L_{crit} = R \times (C_{max} - C_{nat})$ …………………………………………………….…………….…… (11)

$$WF_{grey} = \frac{L}{C_{max} - C_{nat}}$$ …………………………..…………………………….……………..………… (12)

$L = f \times Appl\ (mass/\ time)$ ……………………………………….……………………..……… (13)

$$f = f_{min} + \frac{\sum Si \times Wi}{\sum Wi} \times (f_{max} - f_{min})$$ ……………………………….……………………………… (14)

$$WF_{feed}[a,c,s] = \frac{\sum_{p=1}^{n}\left(Feed[a,c,s,p] \times WF^{*}_{prod}[p]\right) + WF_{mixing}[a,c,s]}{Pop^{*}[a,c,s]}$$ ………….……. (15)

$$WF^{*}_{Prod}[p] = \frac{P[p] \times WF_{prod}[p] + \sum_{n_e}(T_i[n_e,p] \times WF_{prod}[n_e,p])}{P[p] + \sum_{n_e} T_i[n_e,p]}$$ ………………………… (16)

$$\text{Feed}\,[a;c;s] = \text{FCE}\,[a;c;s] \times P\,[a;c;s] \quad (17)$$

Water footprint of hides and skins:

$$WF_{Animal}\,[a;c;s] = WF_{feed}\,[a;c;s] + WF_{drink}\,[a;c;s] + WF_{serv}\,[a;c;s] \quad (18)$$

$$WF_{Product} = \frac{WF_{Animal[a,c,s]} \times W_{Animal} \times DP \times P_f}{W_{product}} \quad (19)$$

$$DP\,(\%) = \frac{\text{Chilled carcass weight}}{\text{Live weight during slaughtering}} \times 100 \quad (20)$$

$$P_f = \frac{W_{product}}{W_{animal}} \quad (21)$$

Water footprint of tannery:

$$WF_{tannery} = WF_{blue,\,tannery} + WF_{grey,\,tannery} \quad (23)$$

$$WF_{blue,\,tannery} = \frac{\sum_{s=1}^{k} WF_{proc,blue}\,[s]}{P[p]} \quad (24)$$

$$WF_{proc,\,blue}\,[s] = (UR \times AP)/100 \quad (25)$$

$$WF_{grey,\,tannery} = \frac{\sum_{s=1}^{k} WF_{proc,grey}[s]}{P\,[p]} \quad (26)$$

$$WF_{proc,\,grey\,[s]} = \frac{L}{C_{max} - C_{nat}} \quad (27)$$

$$WF_{proc,\,grey\,[s]} = \frac{Effl \times C_{eff} - Abst \times C_{act}}{C_{max} - C_{nat}} \quad (28)$$

Water footprint of worker:

$$WF_{worker} = WF_{worker,\,blue} + WF_{worker,\,grey} \quad (29)$$

$$WF_{worker,\,blue} = \frac{\sum_{s=1}^{k} WF_{worker,blue}\,[s]}{P\,[p]} \quad (30)$$

$$WF_{worker,\,grey} = \frac{\sum_{s=1}^{k} WF_{worker,grey}\,[s]}{P\,[p]} \quad (31)$$

Symbols

Abst	: Water Abstraction Volume
AP	: Amount of Production
Appl	: Application Rate of Fertilizer
BOD	: Biological Oxygen Demand
C	: Concentration of Pollutant
CWD	: Crop Water Demand
DO	: Dissolved Oxygen
DO_5	: Dissolved Oxygen after 5 days
DP	: Dressing Percentage of animal
Effl	: Effluent Volume
ET_o	: Reference Evapotranspiration
f	: Fraction (leaching, bacterial)
FCE	: Feed Conversion Efficiency
IR	: Irrigation Requirement
L	: Pollutant Load
L_{crit}	: Critical Load
P	: Precipitation or Rainfall
P_{eff}	: Effective Precipitation or Rainfall
P_f	: Product Fraction
P[p]	: Population of Product
Pop	: Population of Animal
R	: Run off Water
T_i	: Product Import
UR	: Usage Rate
V	: Volume
W_{Animal}	: Weight of Animal
$W_{Product}$	: Weight of Product
WA	: Water Available
WD	: Water Demand
WF	: Water Footprint